Lunar Surface Systems Concepts Studies

THERMAL ENERGY STORAGE FINAL PRESENTATION

Robert S. Wegeng (PI)

James H. Saunders (Co-PI)

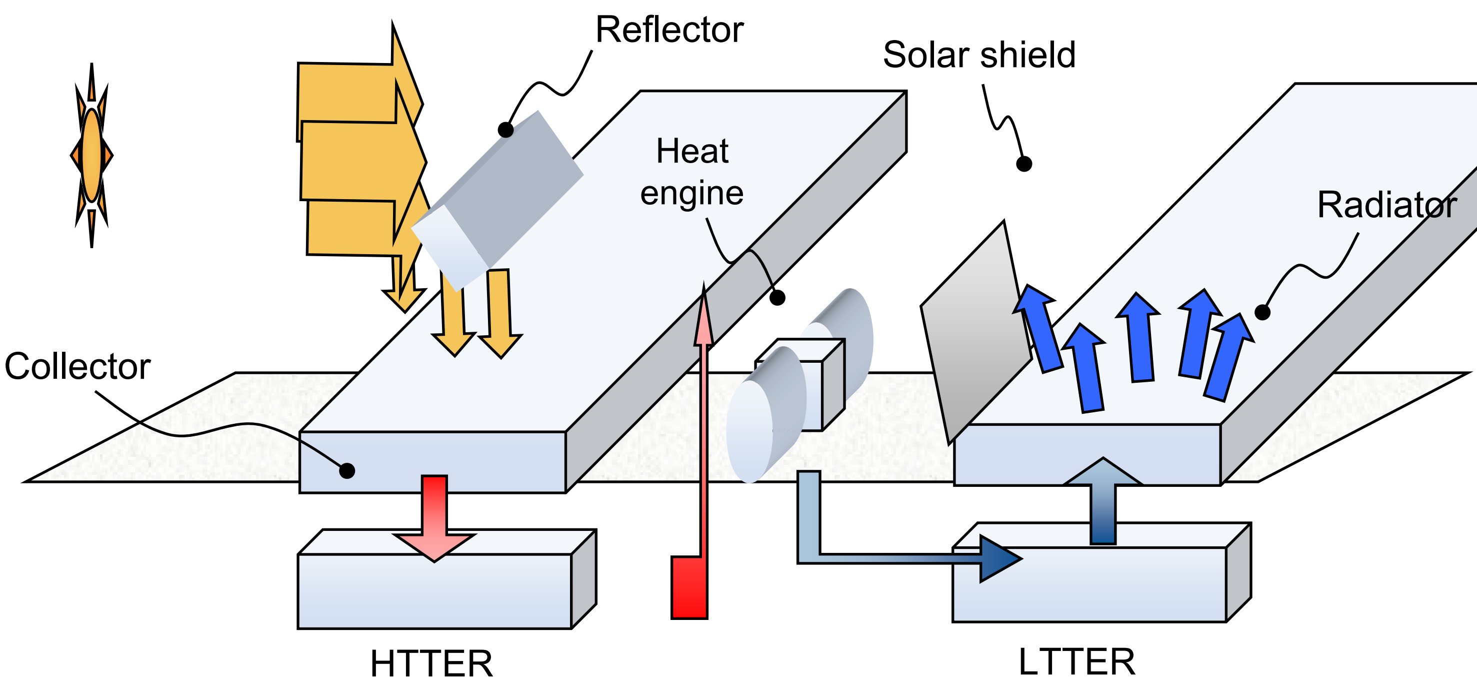
Christopher J. Pestak

Ioan I. Feier

Paul Humble

February 3, 2009

TER System Concept



TER – Thermal Energy Reservoir
HTTER – High Temperature Thermal Energy Reservoir
LTTER – Low Temperature Thermal Energy Reservoir

Reference TER System Conceptual Design for Polar Outpost

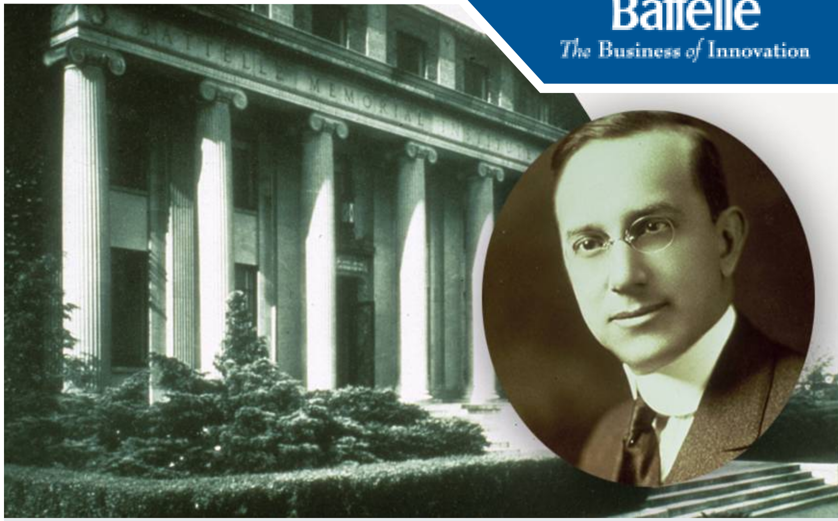
- Makes use of Altair Lander propellant tanks
- Makes use of ISRU byproducts (e.g. from O2 generation)
- Requires no reactants to be brought from Earth
- Net power generation capacity: 2.0 kWe
- Net Power Density: ~10 watts/kg

Outline

- Introduction
- Battelle Overview
- Technical Background
- Analytical Support for Reference System Conceptual Design
- Alternative Radiator Concept
- Additional Applications of Lunar TERs (Not part of Contract Scope)
- Conclusions

Why We Do What We Do – Battelle's Beginnings

- Founded by Will of Gordon Battelle in 1929 as a non-profit, charitable trust to provide "the greatest good to humanity"
- Governed by a self-perpetuating Board of Directors
- Interprets Will in light of today's needs and conditions



Purposes outlined in Will:

- "Creative and research work"
- "Making of discoveries and inventions"
- Better education of men and women for employment
- Societal and economic impact

Battelle
The Business of Innovation

What We’ve Done – Where We’ve Been

- Developed new materials
- Improved and created entire industries
- Pioneered new technologies

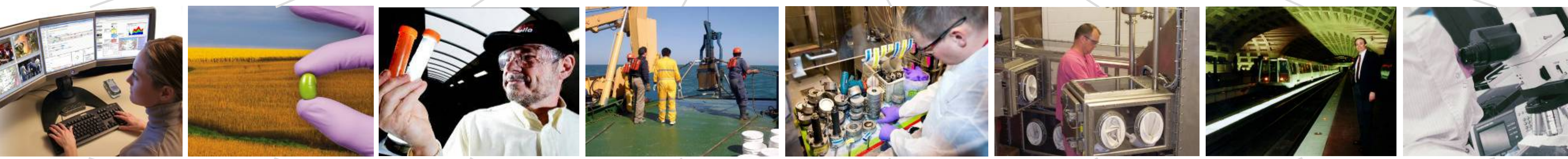
- Metals and materials including armor plating for U.S. tanks in WWII
- Fuel for *Nautilus*, the first nuclear submarine
- *Xerography*
- Early compact disc technology
- Fiber-optics technology for telecommunications
- Increased fuel cell performance and fuel cell materials
- Affordable clean water purification
- Drug delivery technology
- Threat detection for people/infrastructure

Why We Do What We Do – Community Benefit

- “Simultaneous Excellence” and “Community Benefit” are “bookends” of Battelle operations
- We are redefining how the “engaged corporation” interacts with the community
- We promote STEM (science, technology, engineering, and math) education through local, regional, and national programs
  - Emphasis on STEM education will ensure nation’s competitive edge and help sustain our quality of life

- “Portfolio” approach focusing on education, the arts, health and human services, and economic development
- Staff-driven “Team Battelle” volunteer program
- Strategic philanthropy is integrated in Battelle’s business model

Large Company & Vision



Large Network of People and Technology

Large Opportunity to Make More Impact

Technical Background

Bob Wegeng

Battelle - PNNL

Technical Background

Requirements

- 2 to 5 kW_e net discharge electric power
- 100 to 2000 kW_e-hr net energy storage per module
- TRL 6 by 2015 – 2018 timeframe
- Operational life of 10,000 to 15,000 hours
- 100 to 2000 charge/discharge cycles
- Ability to withstand high dust, radiation and widely varying thermal environment

Motivations

- Thermal Energy Reservoirs utilize the diurnal cycle of the Moon to generate electricity
  - Temperature swings of ~100 K to ~400K (equatorial regions)
  - With concentrated solar energy, the high temperature reservoir can be made to be hotter
- The majority of the mass of a lunar TER is already on the Moon

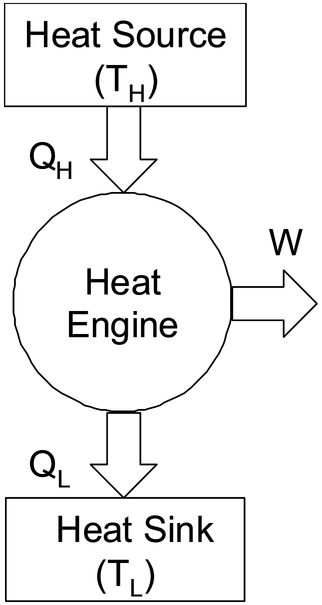
Motivations

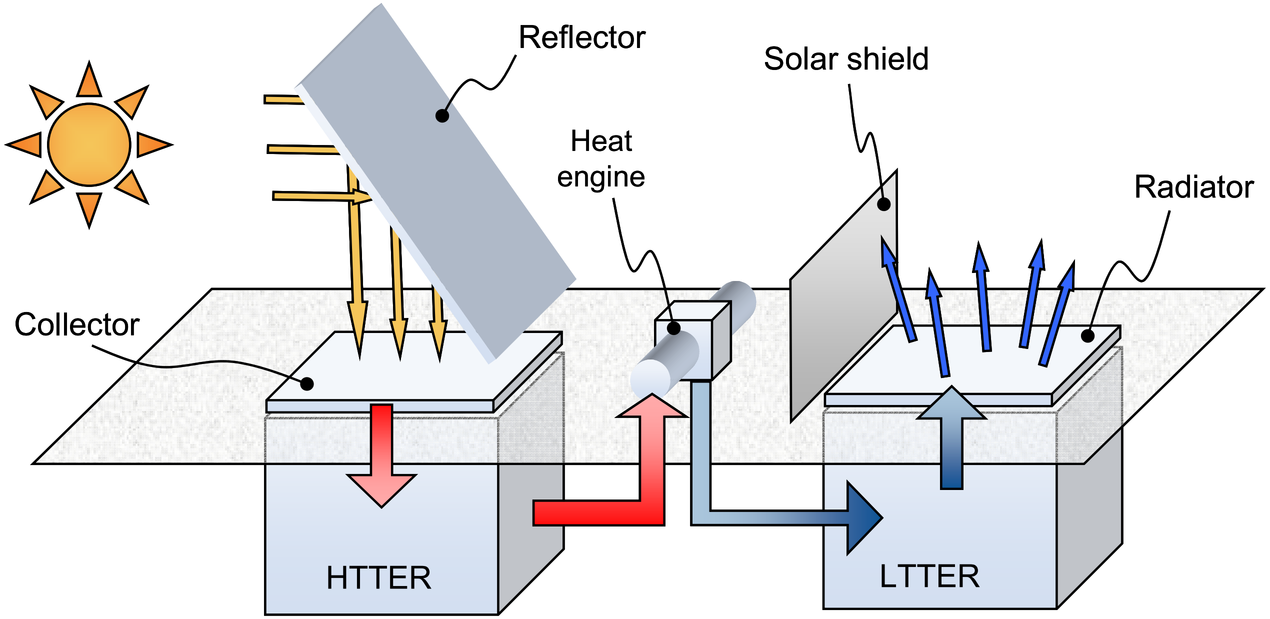
- Synergistic with other lunar assets/programs
  - Considers using processed lunar regolith, a byproduct of ISRU, as thermal mass material
  - Considers using Altair Descent Stage propellant tanks to house thermal mass
  - Considers use of high efficiency Stirling Cycle heat engine
    - International Lunar Network
    - Terrestrial solar-thermal power generation

Courtesy of Infinia Corporation

Technical Background

Thermal Energy Storage Concept





Technical Background

Thermal Mass (TM) Materials

- Native lunar regolith is a poor thermal mass material
  - Thermal properties similar to fiberglass insulation
- Regolith can be processed to yield improved thermal properties

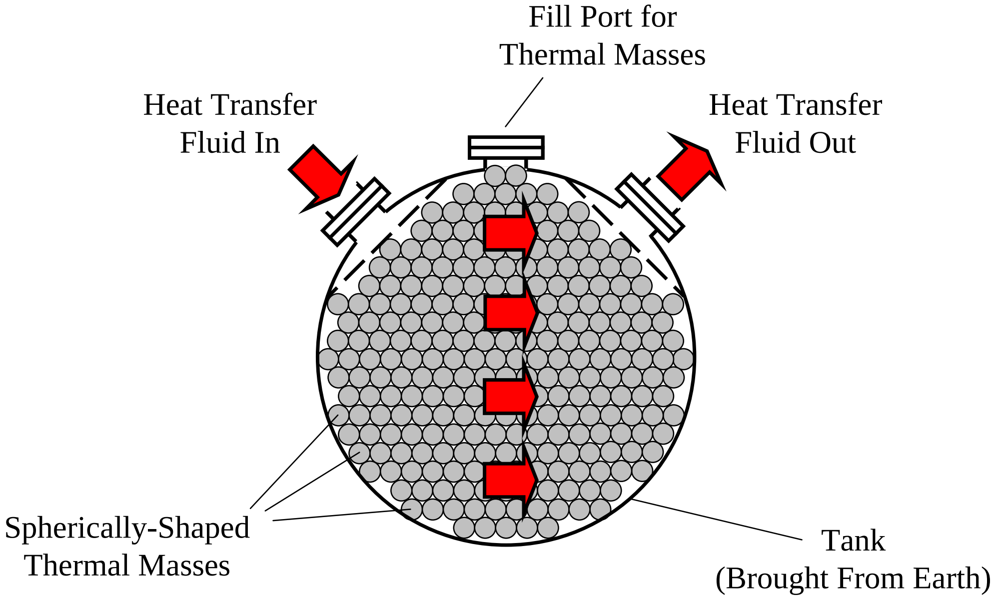
THERMAL PROPERTIES

MATERIAL	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Diffusivity (m^2/sec)	Thermal Interaction Distance over 354 hours (m)
Native Lunar Regolith	1.8×10^3	8.40×10^2	6.6×10^{-9}	0.183
Solid Basalt Rock	3×10^3	8.00×10^2	8.7×10^{-7}	2.11
Common Brick	1.92×10^3	8.35×10^2	4.49×10^{-7}	1.51

Technical Background

Thermal Mass Production Methods

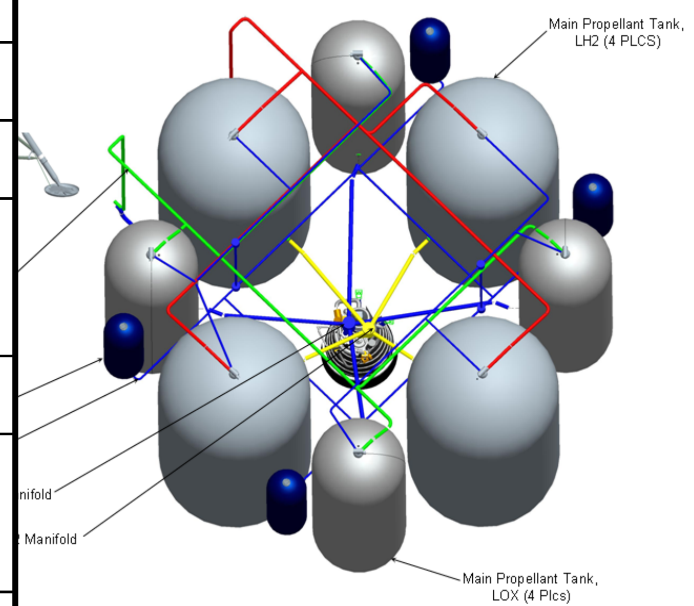
- Compaction and sintering (e.g., microwave sintering)
- Melting processed or unprocessed regolith, then solidifying the melt into a solid block
- Incorporating hardware and/or materials with high thermal conductivity and/or high thermal capacity (e.g., heat pipes, phase-change materials)
- Reducing regolith by thermochemical or electrochemical means, to produce a metal-enriched product



LSAM/Altair Descent Stage LOX/H2 Tank Volume Estimates

	Tank Void Volume*	Thermal Mass Capacity		
	m^3	m^3	kg	kw-hr_t per 100 C
1 O^2 tank	5.655	3.393	8143	185.5
1 H^2 Tank	16.745	10.047	24,113	549.2
1 H^2 tank + 1 O^2 tank	22.40	13.44	32,256	734.7
2 H^2 tanks	33.49	20.094	48,256	1098.5
2 H^2 tanks + 1 O^2 tank	39.145	23.487	56,369	1284.0
2 H^2 tanks + 2 O^2 tanks	44.8	26.88	64,512	1469.4

Descent Module Main Propulsion System



* Provided by Kriss Kennedy and Gary Spexarth, email 12/11/2008

16

Example Capacity Calculation (Approx)

- *What power level can be obtained while extracting heat in a way that decreases the temperature of the HT TER by 100 C?*
- Assume 1 H_2 tank + 1 O_2 tank

  32,256 kg thermal mass

  734.7 kw-hr$_t$ per 100 C
- Assume 20% efficient heat engine operating for 52 hours, with 90% shaft-work to electricity efficiency

  Power = 734.7 kw-hr$_t$ x 0.20 / 52 hours = 2.83 kW$_{\text{shaft work}}$

  = 2.54 kW$_e$

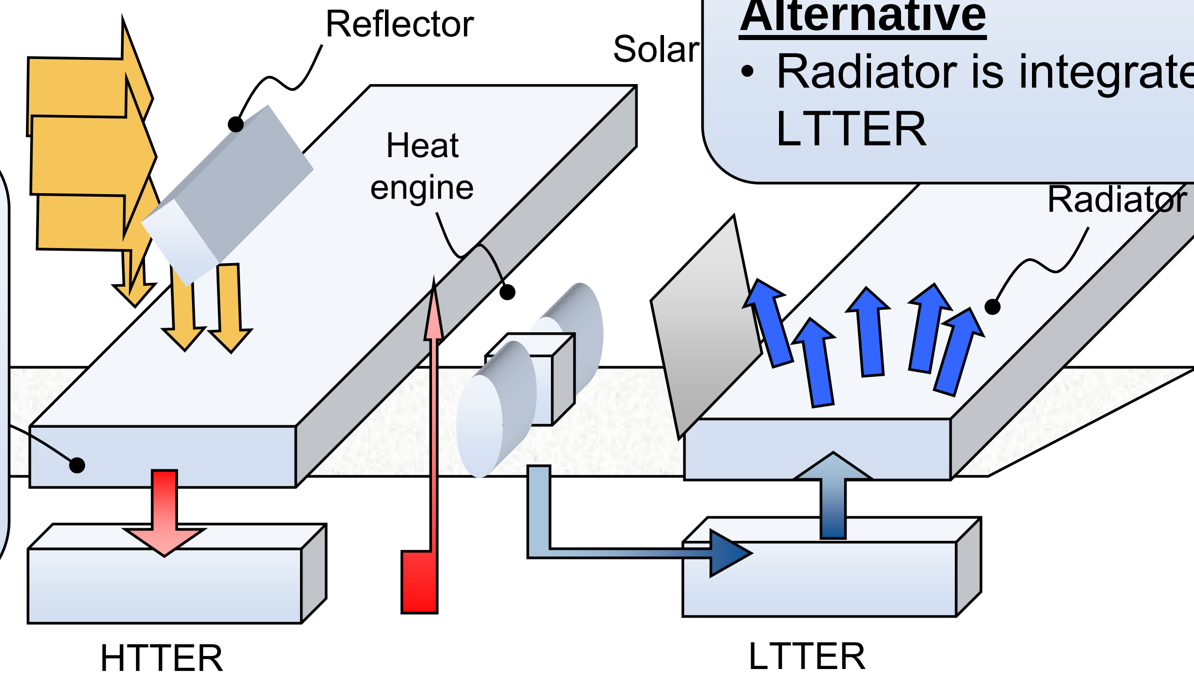
Reference System Configuration

Reference System
- Stirling Cycle Heat Engine

Reference System
- Radiator with Solar Shield

Alternative
- Radiator is integrated with LTTER

Reference System
- Thin-Film Concentrator (above ground) with Flat Plate Collector



Reference System
- TM consists of Processed Lunar Regolith

Reference System
- TM in Propellant Tanks

Alternative
- TM is integrated with Radiator

Analysis Supporting Reference Conceptual Design

Jim Saunders
Battelle - Columbus

Analytical Approach

- Goal: Develop system models to estimate mass, volume and performance of thermal energy storage module based power systems for the lunar night.
- System models
  - Lumped parameter models based upon component description
    - Subsytem or component models or parameterizations
  - Simulate charging of the TER during the lunar daytime and power generation during the night.
- Calculations with encouraging power densities.

Thermal storage advantage

- Compare two energy storage approaches:
  - 1) launch mass is mainly proportional to stored energy (P*t).
    - Batteries
    - Fuel cells
  - 2) launch mass is mainly proportional to required power
    - Regolith thermal storage with heat engine

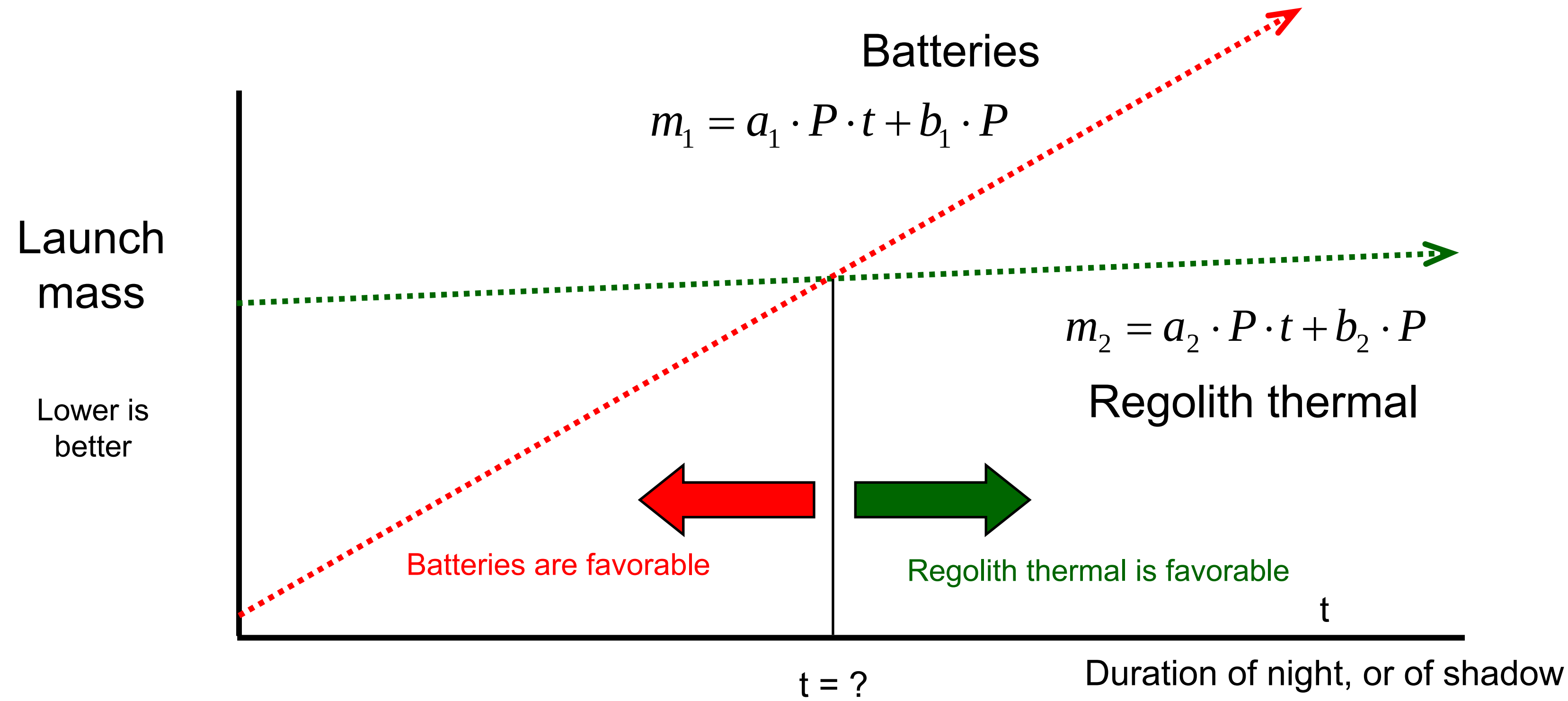
$$m_1 = a_1 \cdot P \cdot t + \cancelto{\text{small}}{b_1} \cdot P$$

$$\text{mass} = \text{constant} * \text{power} * \text{time} \ + \ \text{constant} * \text{power}$$

$$m_2 = \cancelto{\text{small}}{a_2} \cdot P \cdot t + b_2 \cdot P$$

- In other words imagine two different systems such that b_1 and a_2 are small (relative to b_2 and a_1, respectively)

Thermal storage advantage

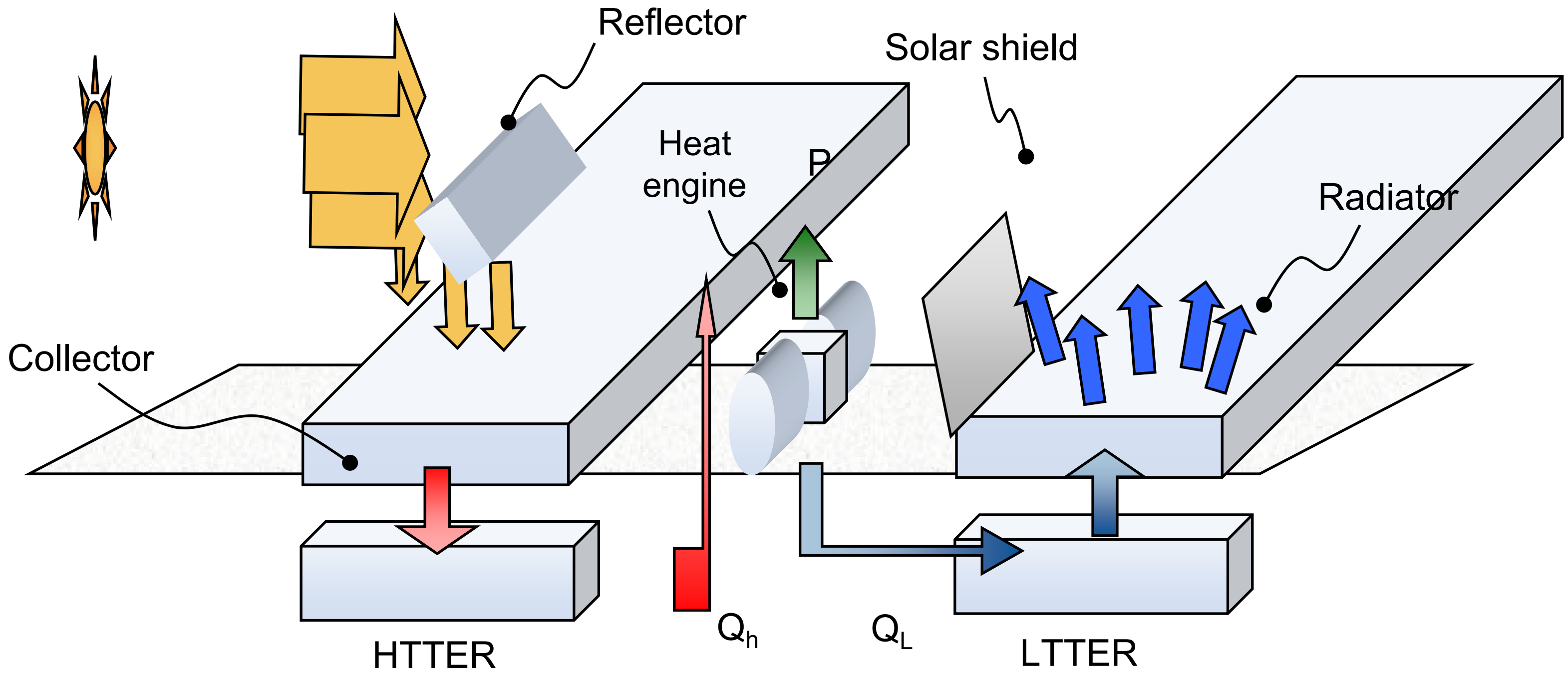


- Constants a & b will never be negative since masses are always positive
- Pick 50% light to dark ratio, square wave, where 2*t is the period of a light and dark cycle
- For some value of t, the regolith thermal approach will have less launch mass
- Conclusion: for long dark periods regolith energy storage is attractive

System Configuration

- Non-polar region: 348 hr day and night
  - Easiest first calculation
- South Pole Shackleton Crater:
  - 52 hr max night. Simulations with 52 hr day and night.
  - Seasonal simulations: more complex.
- Assume 2 kW_e, 90 % power electronics efficiency, 200 W parasitics, which yields 2440 W shaft power.

Configurations



Reference case: Reflector, collector, HTTER, Carnot engine, radiator.

- No LTTER
- Alternate case: LTTER found favorable in previous work.
- Start with generally ideal assumptions for example calculations.
- Optimized the collector and radiator area for each HTTER, LTTER combination.

Solar Collector

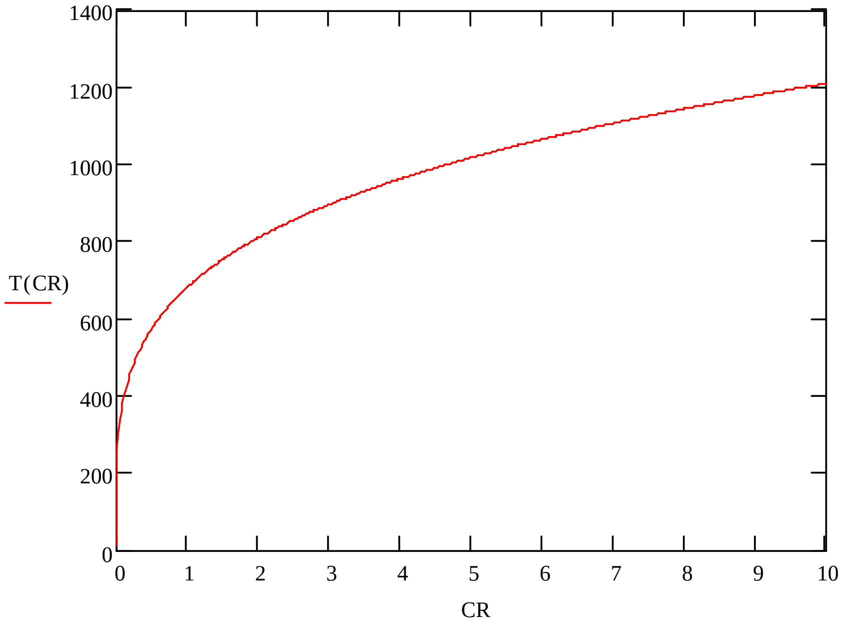
- Flat plate heat exchanger
  - Assume two 1 mm Al sheets: *Allowable stresses suggest that < 1 mm is sufficient. Previously we used 3 mm.*
  - H_2 heat transfer gas from collector to HTTER.
  - Selective surface. Absorptivity =.9, IR emissivity = 0.1
  - Flat, located at the side of the HTTER.
- Reflector directs sunlight to the heat exchanger
  - Assume a 1mm Al sheet with 10 kg for tracking drive and 10 kg for supports.
  - Area=1.2*Concentration Ratio * Area Collector. Reflector and concentrator are combined for our low concentration ratios.
  - Results in 2.7 kg/m^2
    - Kohout (1991) used 2.48 kg/m^2 for a PV array including tracking, wiring, frame
    - Freeh (2008) used 2 kg/m^2 for a PV array with 10 kg for drive and 10 kg for supports.

Solar Collector (cont'd)

- What is the maximum temperature of this collector?
- Ignoring radiation back to the sun:

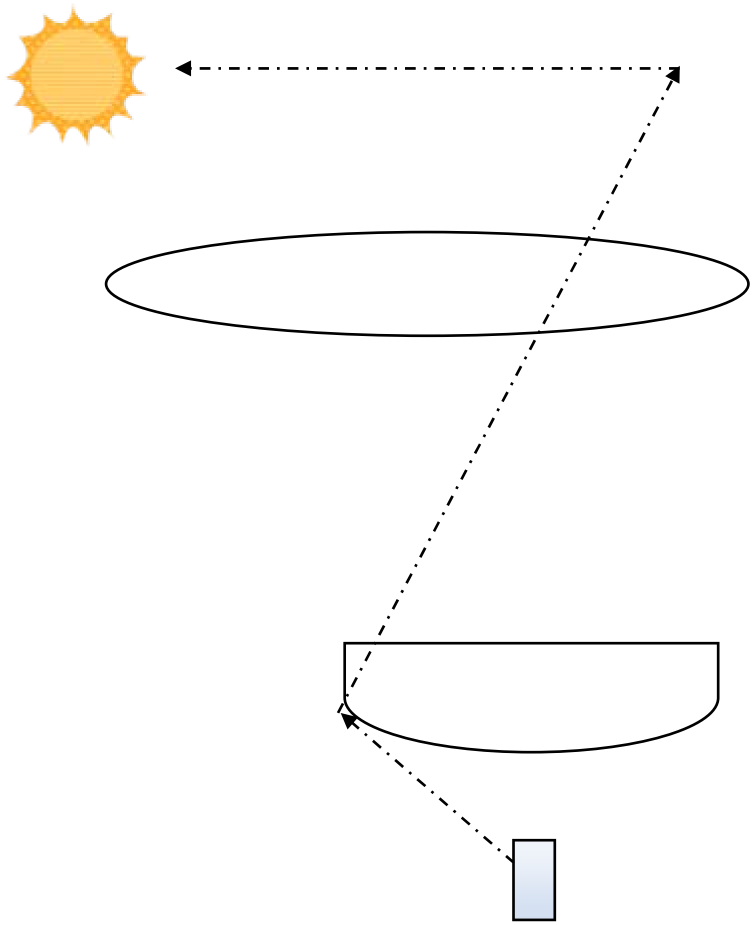
$$q = \alpha q_{sun} CR - \sigma \varepsilon \left(T^4 - T_{amb}^4 \right)$$

- CR is the concentration ratio.
- For the maximum temperature, q=0, and T=680 K for a concentration ratio of 1, and T= 809 K for CR=2.



Advanced Concentrated Collectors

- We have considered flat plate collectors with reflectors that concentrate light.
  - The collectors see a large fraction of deep space for reradiation.
- Concentrated collectors, at the back of a cavity:
  - See more sun for reradiation, reducing thermal losses.
  - We have neglected this effect in our simulations
- More advanced concentrating collectors should be explored in future work.



Processed Regolith Properties

- Uncertainty in properties. Varies with lunar location.
- Processed regolith - Used correlations of Colozza (1991), based on Apollo 17 data.
  - Density: V_F3000 kg/m^3, pick V_F=0.9
  - Specific heat (assumed to be the same for processed and native):
    - C = -1848.5 + 1047.41* log(T) J/(kg*K)
    - Note that for T<58.2 K this fit yields C<0 which is physically unrealistic
  - Thermal conductivity was not needed in the system model. For component models, constant values and temperature dependent functions were both used.
- Discussed regolith properties with GRC staff. Simulants are available for native regolith. Not much available on processed regolith.

High Temperature Thermal Energy Reservoir

- For the system model, assumes a thermal mass maintained at a uniform temperature by the flow of heat transfer fluid through the regolith.
- Component models examined this more carefully.
  - Regolith spheroids arranged within the propellant tank
- Assume the HTTER is a cube of dimension L, surrounded by a radiation shield blanket.
  - Blankets are in use that have effective emissivities ≈ .001 - .005.
  - Protects against micrometeoroids, charge accumulation, plume impingment, corrosion, etc. Charging control may help with dust repression.
- Radiation shield mass is included, but approximate. Assumed equivalent to 2 Al sheets, 0.1 mm thick.
- Neglected heat loss in our simulations, except for one seasonal simulation.
- The collector sits on top and has an area, Ac.

Heat engine

- Carnot engine, K = 1.

$$\eta_{engine} = K\left(1 - \frac{T_L}{T_H}\right)$$

• Assumed 100 W/kg for engine, based upon discussions at GRC

•Stirling engine

•K≈0.6 over a wide temperature range.

•Reviewed Stirling performance & W/kg, with GRC.

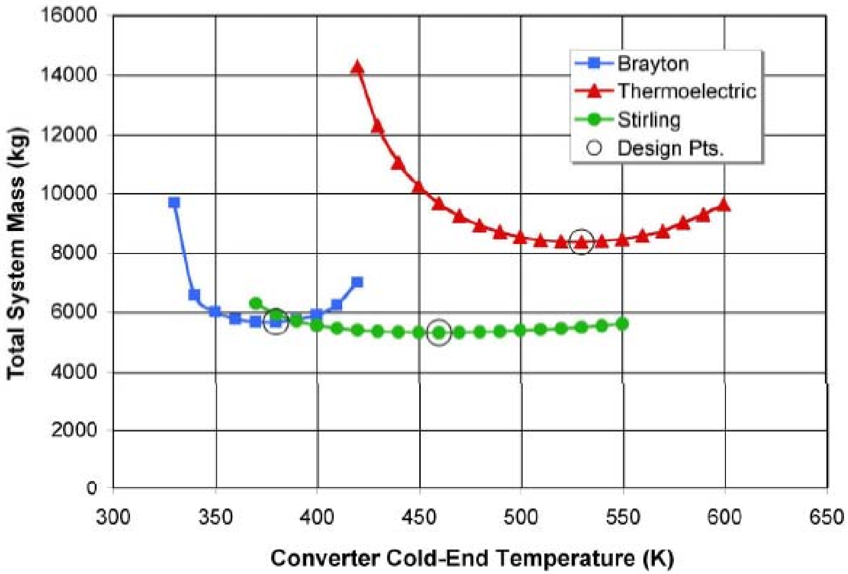
•Usual operating temperature range: $T_L \approx 323$ K.

•Assume engine shuts down for $T_H/T_L < 1.25$.

•For $T_L = 300$ K, $T_H = 800$ K, $\eta_{engine} = 37.5$ %

Stirling Technology

- Example: Lee S. Mason, "A Comparison of Fission Power System Options for Lunar and Mars Surface Applications, NASA/TM-2006-214120
- 50 kW electrical output scenario
- Stirling system has the lowest system mass and best specific power
  - TE: 6.0 W/kg
  - Brayton: 8.8 W/kg
  - Stirling: 9.4 W/kg
- Stirling system has best overall efficiency (Pout/Psource)
  - TE: 4.3%
  - Brayton: 13.9%
  - Stirling: 19.0%
- Stirling has broad operating range and can function effectively over temperature ratios as low as 2.0-2.5



•Stirling: 60 % Carnot for $3 > T_H/T_L > 2$

•Brayton: 40 % Carnot for $4 > T_H/T_L > 3$

•Thermoelectric: < 20 % Carnot for $2 > T_H/T_L > 1.5$

•Stirling: ~ 100 W/kg

•(Mason and Schreiber, 2007)

•Stirling has run to $T_H/T_L \approx 1.5$. Assumed 1.25 for the analysis. No upper limit.

Radiator

- Two 1 mm sheets of Al
- Area density of 5.3 kg/m^2.
- 5 kg/m^2 used by others (Kohout, 1991; Freeh, 2008)
- Sink temperature assumed to be 10 K, with one side of active area.
- Mason has looked at vertical two-sided radiators with higher effective sink temperatures.
- Inflatable radiators ~ 1 kg/m^2 (Wong, GRC).
- We propose an additional radiator concept.

Low temperature thermal reservoir

- Can reduce radiator size
- In contrast to HTTER, we want to maximize heat loss. This implies large surface to volume ratio and low surrounding temperatures.
- Located in the shadows or cooled by heat rejection to dark sky at ≈ 10 K.
  - Summer or winter.
- Assumed to start at 150 K.
- Shadowed base of Shackleton crater ≈ 90 K, according to recent Japanese measurements.

Parasitic Power

- Assumed four heat transfer loops using H_2.
  - Collector to HTTER
  - HTTER to engine
  - Engine to LTTER
  - LTTER to radiator
- Compressor with motor mass assumed to be 15 kg for all cases. Four compressors assumed.
  - Based upon H_2 Autorotor twin-screw compressors (without motor).

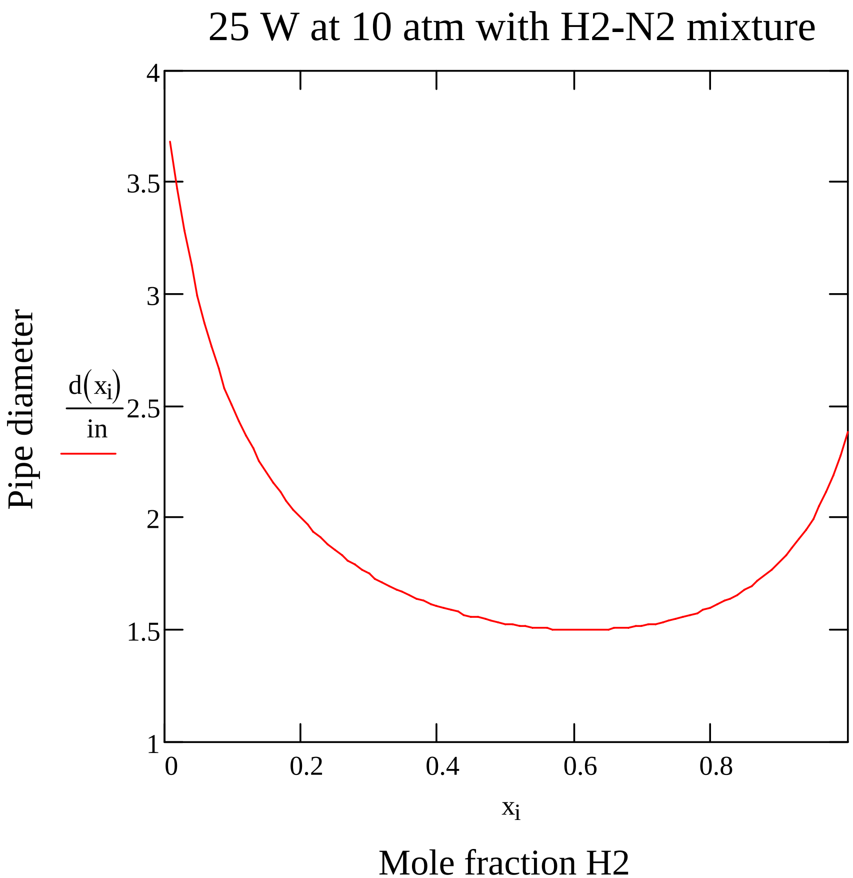
Assumed 75 % motor efficiency, 60 % impeller efficiency in the model.

	Flow	Pressure	Mass	Pressure ratio
Autorotor OA3150	380 g/s	2.7 bar	15 kg	2
Autorotor OA1050	100 g/s	2.7 bar	5.7 kg	2
Battelle	~100 g/s	10 atm	15 kg with motor	Small

Parasitic Power (cont'd)

$$d(x) := \left[\frac{4.f \cdot L}{\pi \cdot \rho(x)^2 \cdot Pwr} \cdot \left(\frac{Q_{coll}}{c_p(x) \cdot DT}\right)^3\right]^{\frac{1}{5}}$$

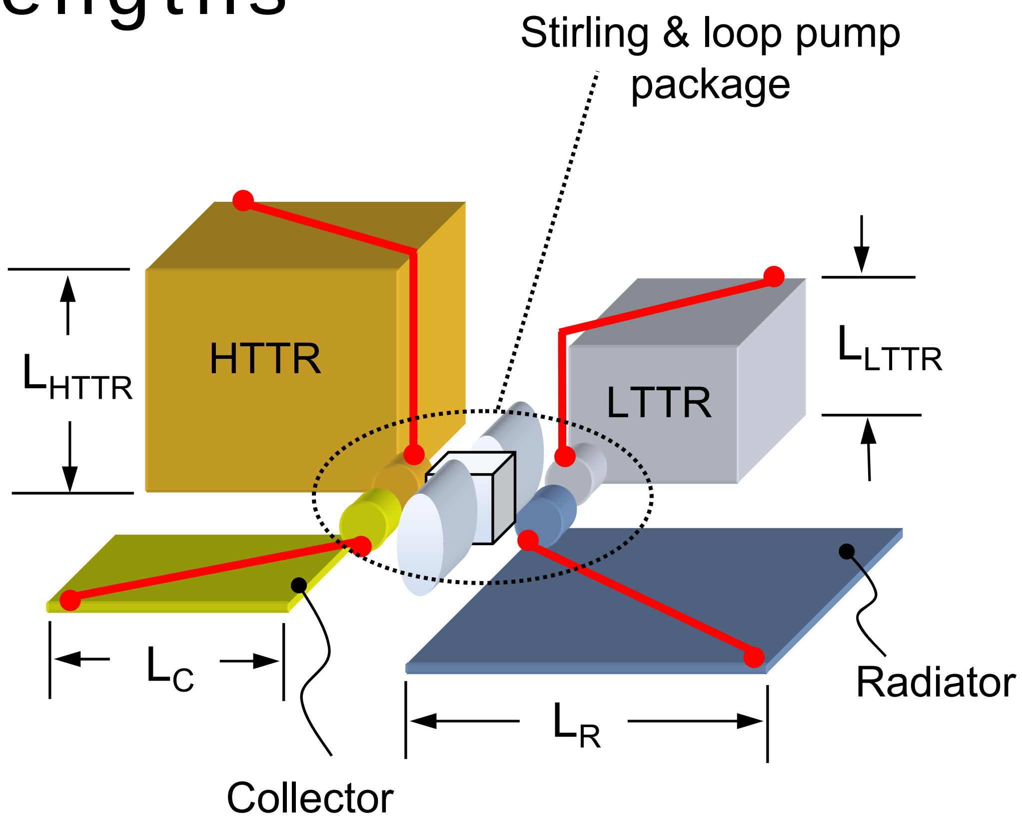
- Mixtures of H_2 - N_2 or H_2 - Xe, etc may give lower parasitic losses.
- Water could be used in the low temperature loops if the radiator temperature is held above 273 K.



Parasitic Power (cont'd)

- **Mass of heat transfer fluid: H_2 for HTTER, H_2 or water for LTTER?**
  - Volume of HTTER = 16.75 m^3
  - Assume 40 % void fraction
  - Mass of H_2 at 10 atm required for HTTER tank = 2.33 kg
  - Volume of LTTER = 10,000/2700*.4/.6 = 2.5 m^3
  - Mass of water required: 2,500 kg
  - Mass of H_2 required: 2 kg
  - Therefore we selected H_2 for the base case in both the HTTER and LTTER.
  - Mass of H_2 is neglected in system calculations

Piping Lengths



Solar collector to HTTR fluid loop pipe length:	$L_C\sqrt{2}$
HTTR to hot side of Stirling engine fluid loop:	$L_{HTTR}\left(\sqrt{2}+1\right)$
Cold side of Stirling to LTTR fluid loop:	$L_{LTTR}\left(\sqrt{2}+1\right)$
LTTR to radiator fluid loop:	$L_R\sqrt{2}$

Model formation

- Collector and HTTER described by T_1.
- Radiator and LTTER described by T_2.

$$m_1 c_1 \frac{dT_1}{dt} = Q_{collector} - Q_{engine} - Q_{loss}$$

$$m_2 c_2 \frac{dT_2}{dt} = \left(1 - \eta_{engine}\right) Q_{engine} - Q_{rad} - Q_{lossrad}$$

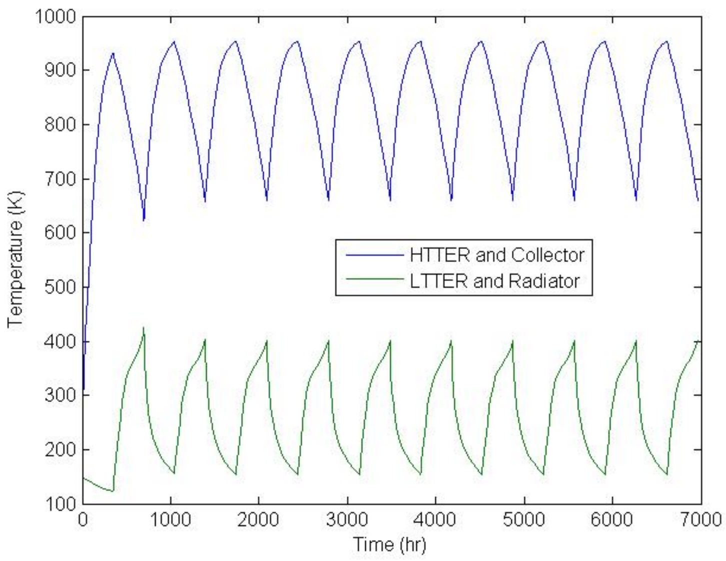
•Used an explicit approach to model heat transfer loops.

•**Pipe sizing and parastics**. Modeled 4 heat transfer fluid loops, all using H_2. Sized pipe diameters to hold ΔT to 10 K and parasitic power to 200 W total. Calculated power and ΔT at each time step. Checked to see that targets were achieved.

•With ΔT small compared to $T_H - T_L$, ΔT is neglected in the power calculation.

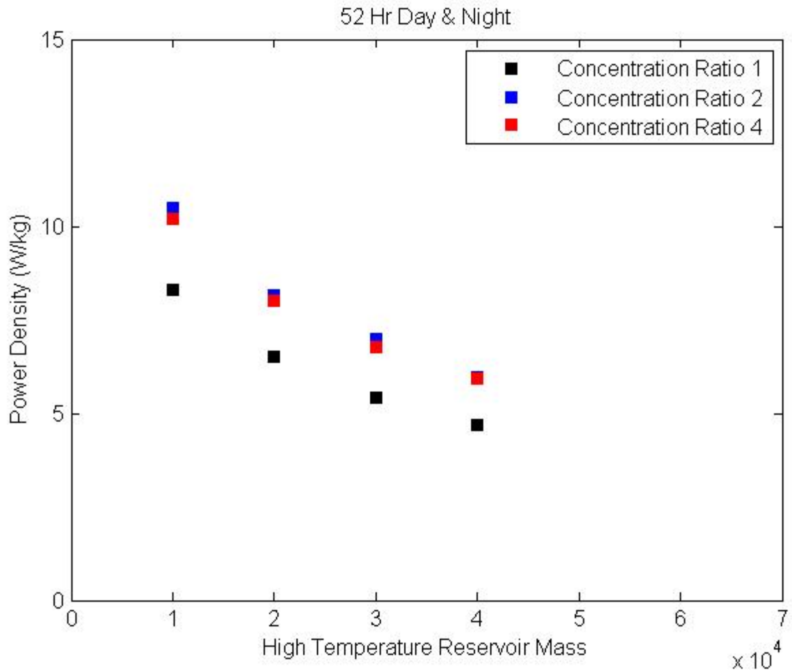
System Analysis

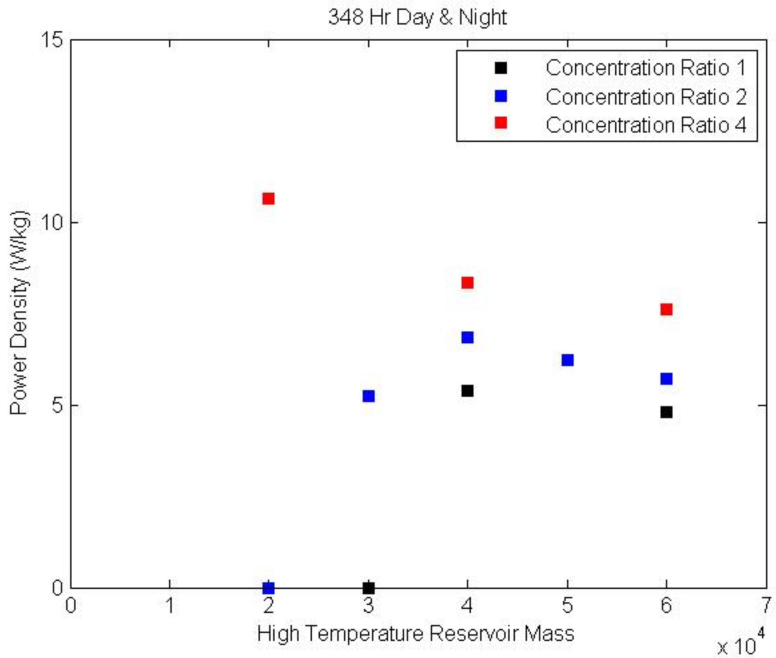
- Careful check of energy balances.
- System cycled through 10 day/night cycles to achieve steady-state. Tabulated energies on last cycle.
- Varied (Ac, Ar) to get maximum power density for each HTTER, LTTER combination.
- Found maximum power density for two cases:
  - $T_L > 270$ K. Usual operation is $T_L \approx 323$ K.
  - Any T_L



Overall Power Density

- Each point represents an optimized power density with collector and radiator area as the independent variables.
- 10,000 kg low temperature reservoir for all cases.
- Power is the shaft power (2440 W), not the net electrical power (2000 W).
- Parasitic power is roughly sized for 200 W, but some cases go up to 380 W.
- Temperature drop in heat transfer loops is about 10 K and is neglected in the performance calculation, but is included for the parasitic power.





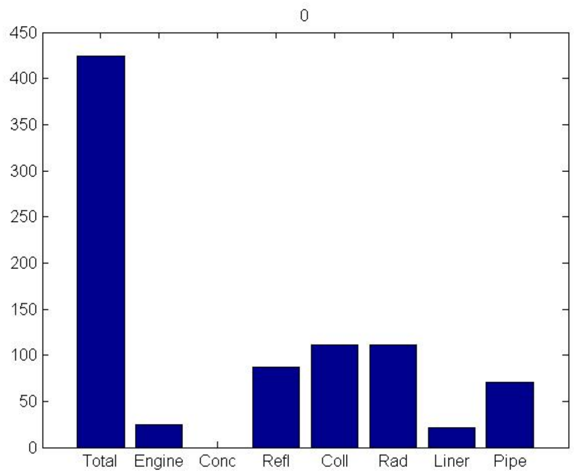
Comparison of Masses

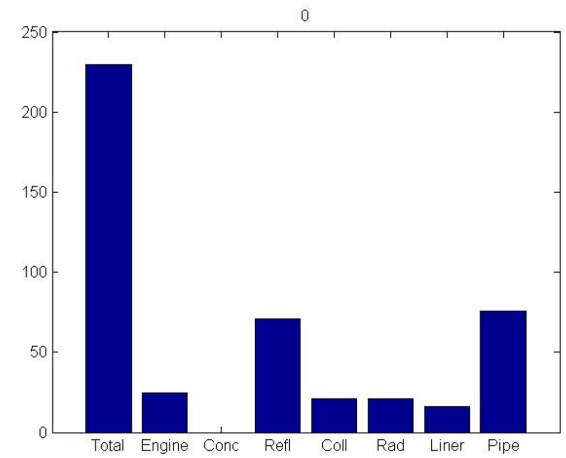
52 hr day and night, Conc R = 1

30,000 kg HTTER

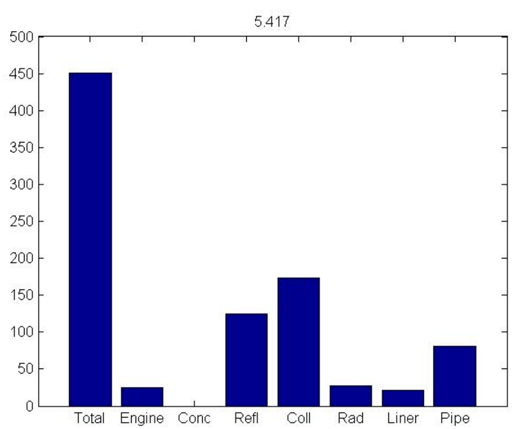
348 hr day and night, Conc R = 4

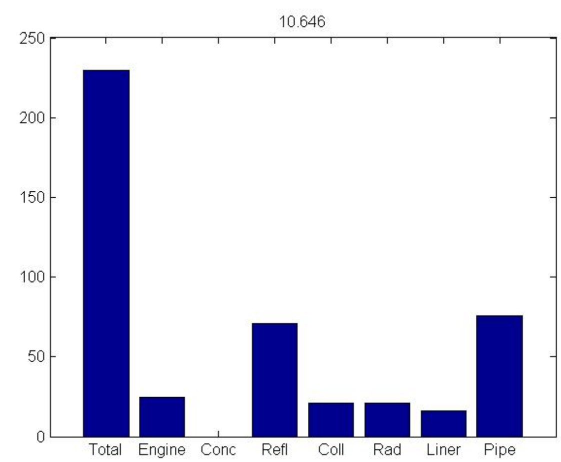
20,000 kg HTTER.





Any Radiator Temperature



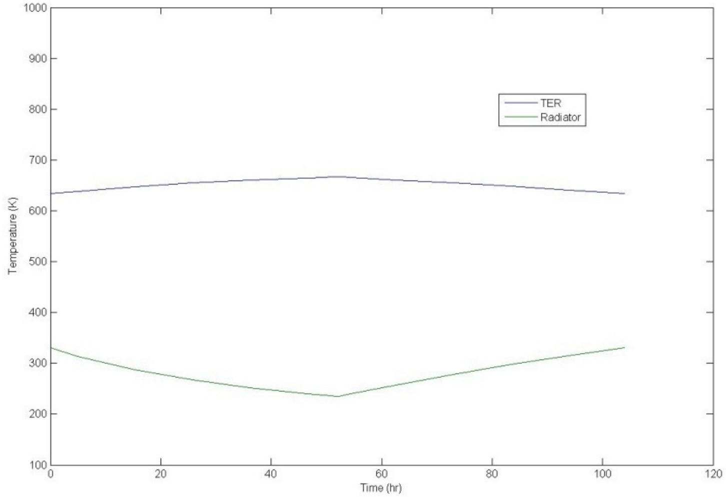


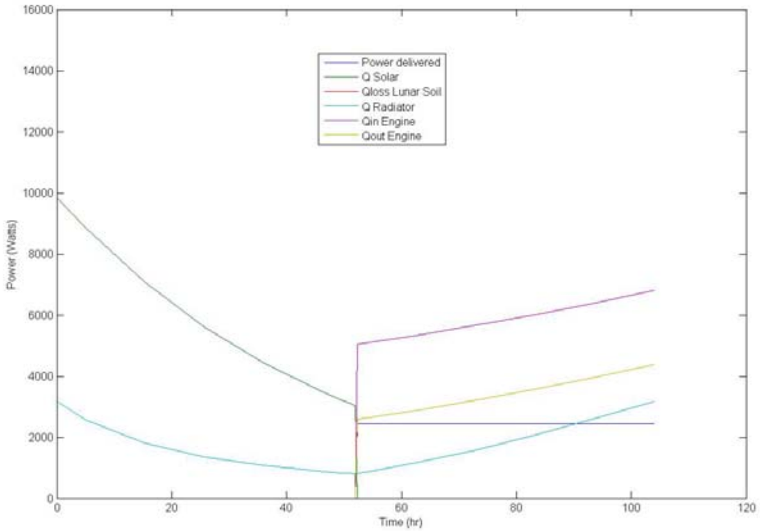
Radiator Temperature > 270

Comparison of Temperatures and Heat Flows

52 hr day and night, Conc R = 1

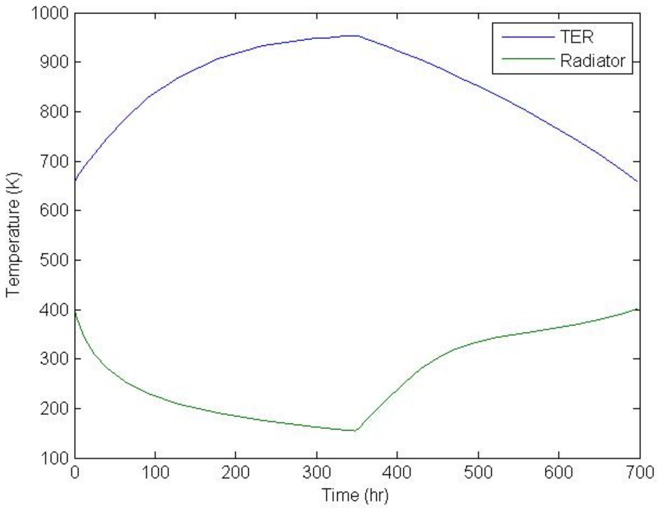
30,000 HTTER

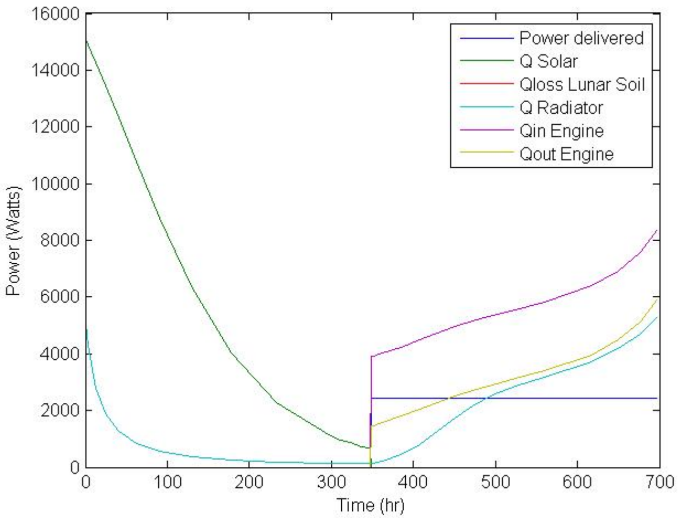




348 hr day and night, Conc R = 4

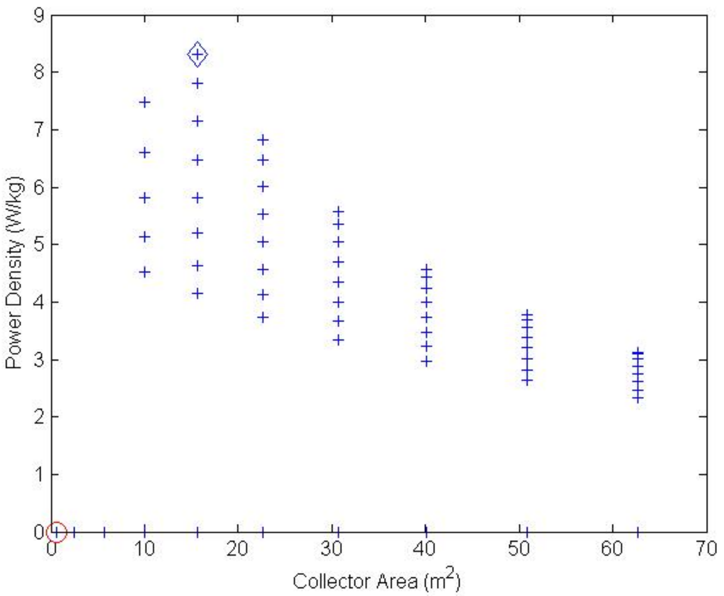
20,000 kg HTTER.

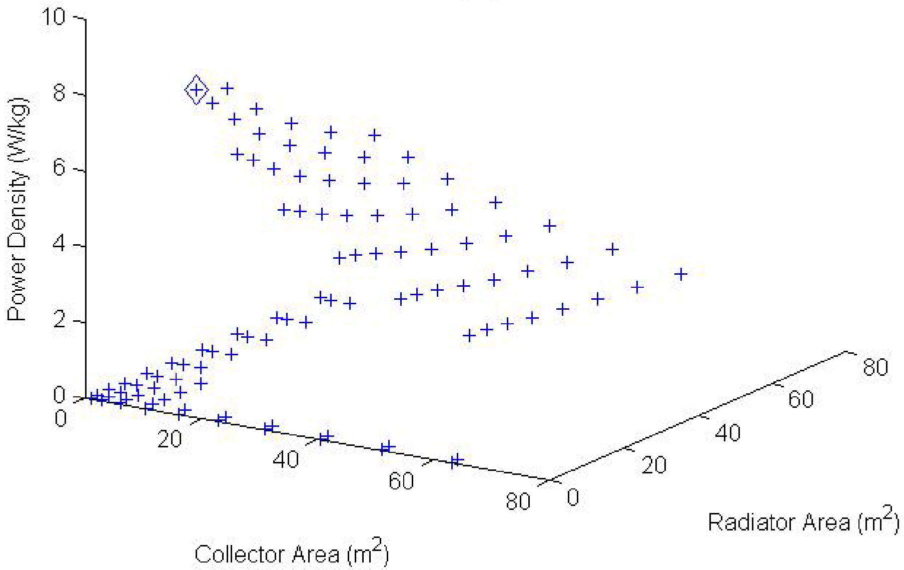




Determination of Best (Ac, Ar)

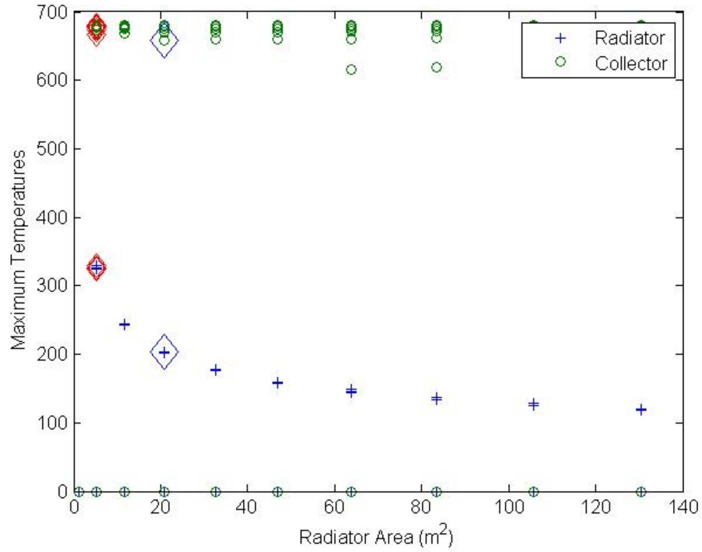
- Note that the engine cannot deliver 2,440 W for all (Ac, Ar).
- Optimum is on the "edge of the cliff".
- Smallest (Ac,Ar) that delivers the power is the best.



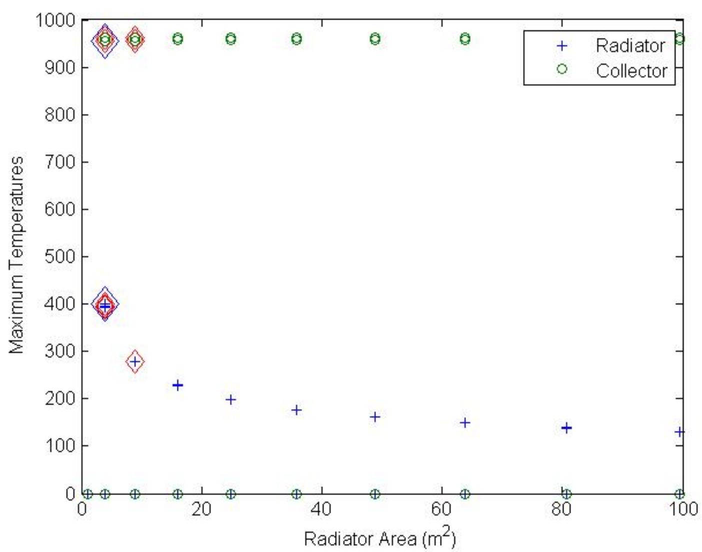


Effect of Radiator and Collector Temperatures

- Radiator temperature is a key variable.
- Generally lower temperatures yield higher power densities.
- Red diamonds show temperatures over 270. Blue diamond at (22,200) is the highest power density.
- Collector temperature is consistently near the maximum.
- The length of the solar daytime will also be important.



52 hr night, Conc Ratio = 1, 30,000 kg HTTER



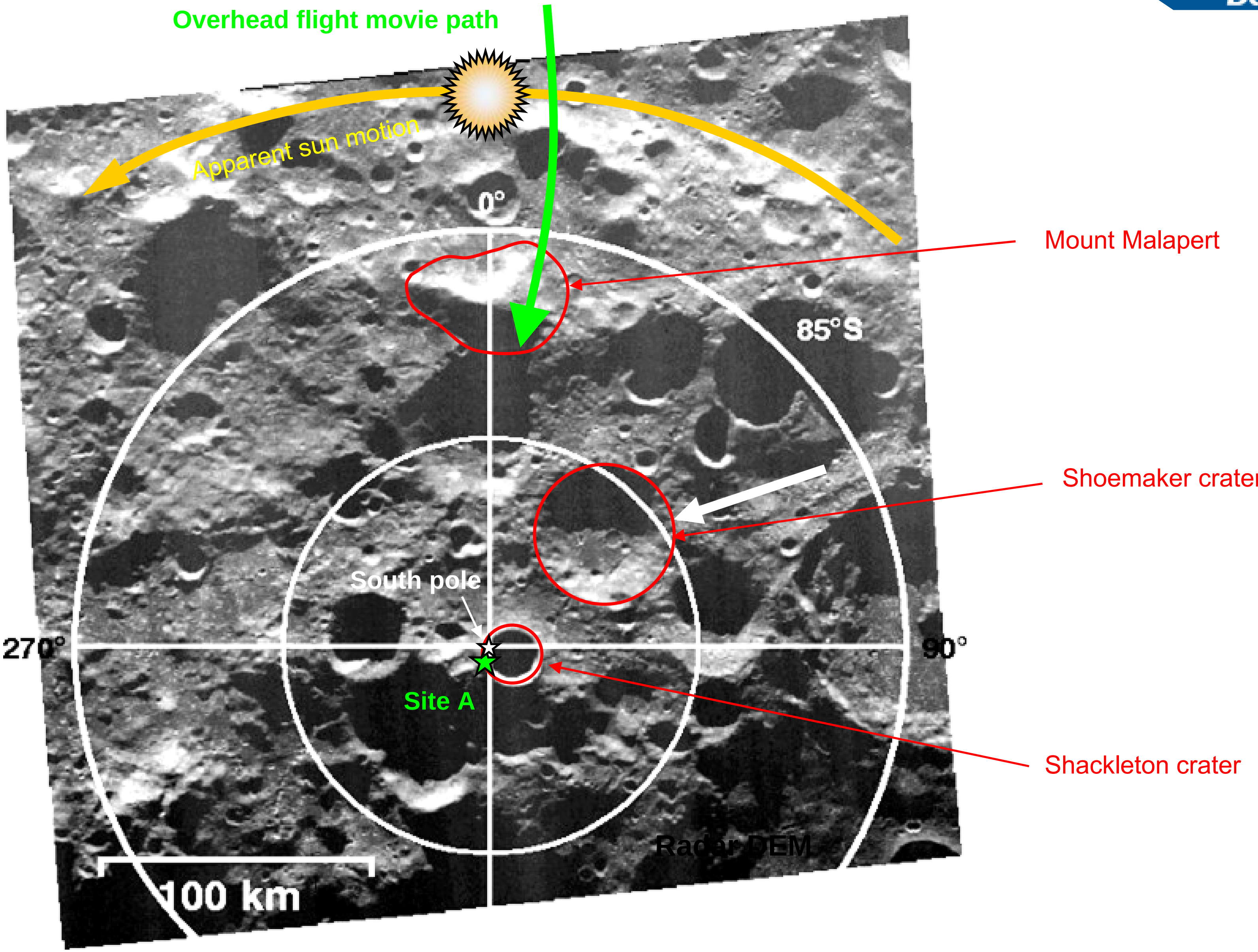
348 hr night, Conc R = 4, 20,000 kg HTTER

Design Guidelines

- Repeating day and night cases.
- At steady state, $E_{HTTER} = P*t/\eta_{eng}$
- Need just enough E_{HTTER} to supply power
- Need T_H and T_L such that the engine runs and with acceptable $\eta_{eng.}$ $T_H/T_L > 1.25$. For $T_L = 323$, $T_H > 404K$ at the end of the night.
- For engine efficiency = 30 %, TH=646 K
- Collector (and T_{HTTER}) has a maximum temperature for a given concentration ratio, which is usually just reached in optimal designs.
  - CR =1, T_H = 680 K.
  - CR=2, T_H = 809 K
  - CR=4, T_H = 962 K
- Larger HTTER masses require larger collectors, longer pipes, more insulation, but have less temperature drop and thus require lower radiator area

Power Density Discussion

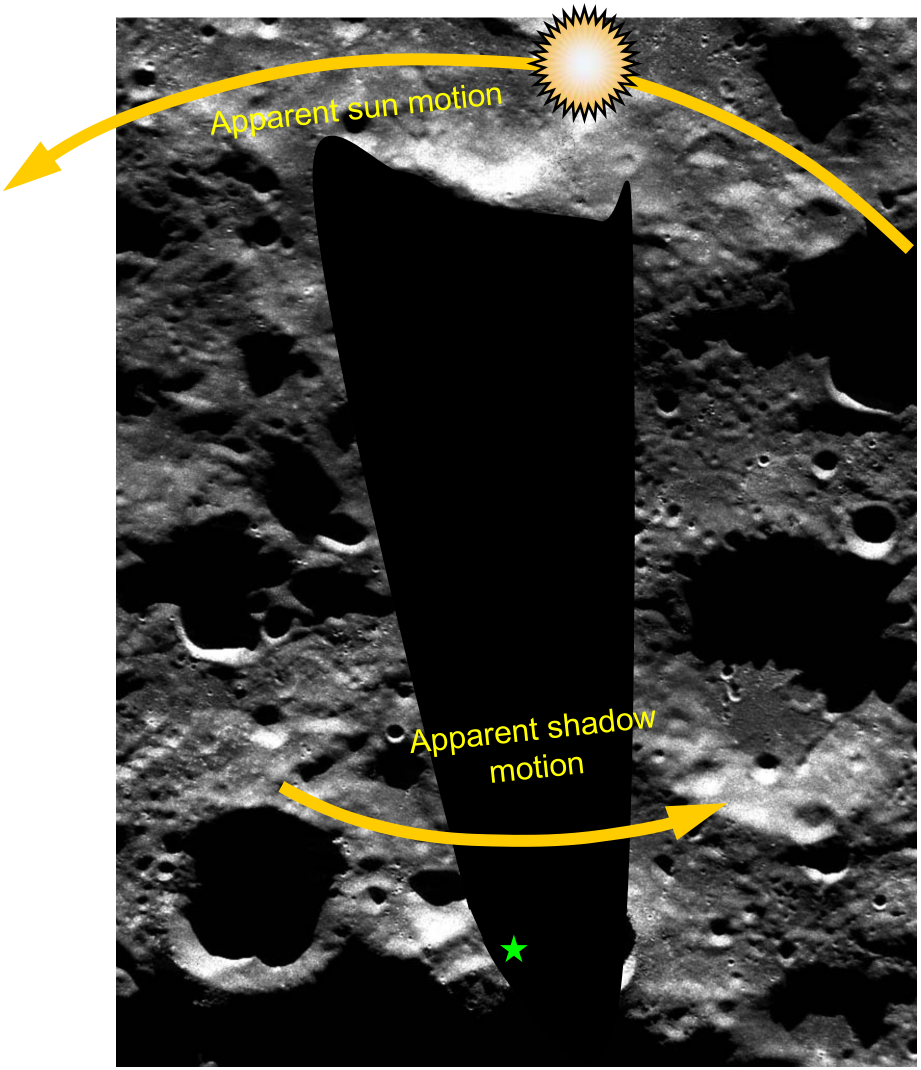
- Power density = Power/Mass Carried
- Power is fixed as long as the engine can deliver it.
- Mass is the key variable.
- Mass comments:
  - Low density radiators and collectors could really help (We're assuming 5.3 kg/m^2 for the radiator, more for the collector– typical number is 5 (Kohout, Freeh). Inflatable radiators could be 1-2.
  - Flow loop design is just roughed in. Assuming H_2 for both fluids. H_2/N_2 or H_2/Xe should be better.
  - Reflector is significant. Now just assuming A=1.2*CR*Ac.

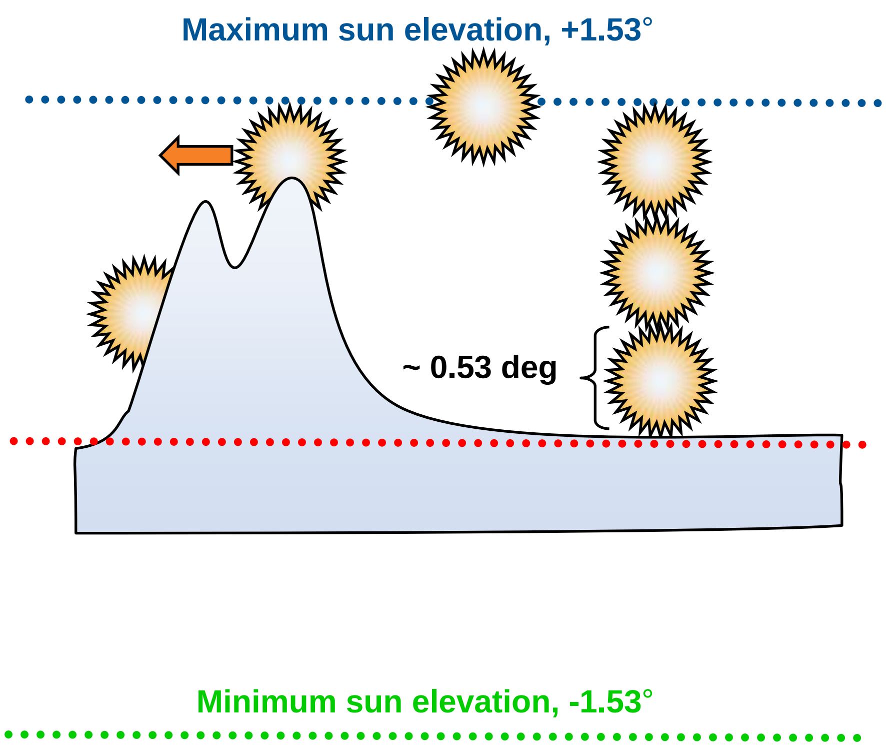


Radar interferometry digital elevation models (DEM) exist

background image from http://lcross.arc.nasa.gov/docs/Allen.LCROSS%20talk.ppt#272,4,Slide 4 (Carlton Allen, NASA JSC)

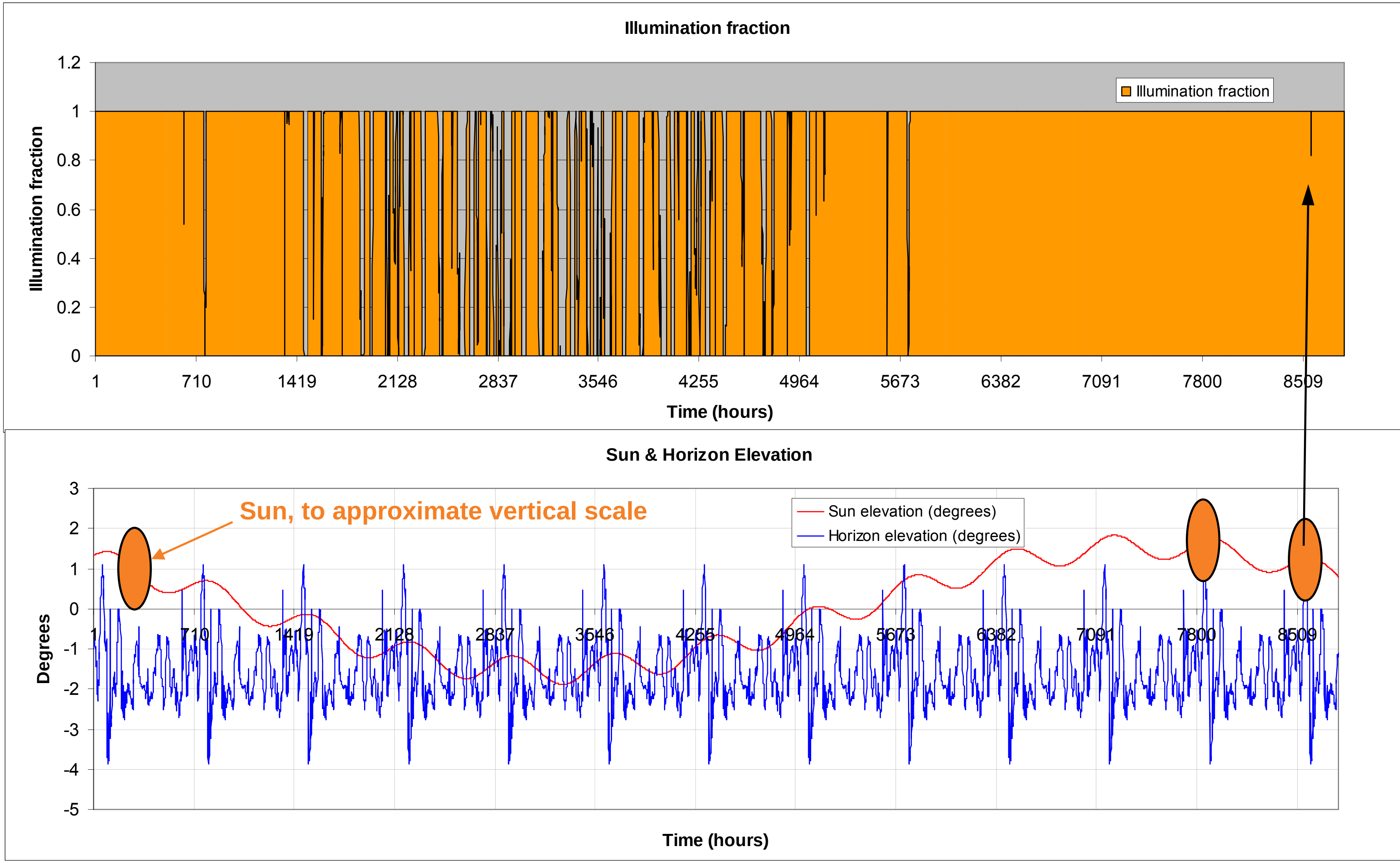
Shadowing





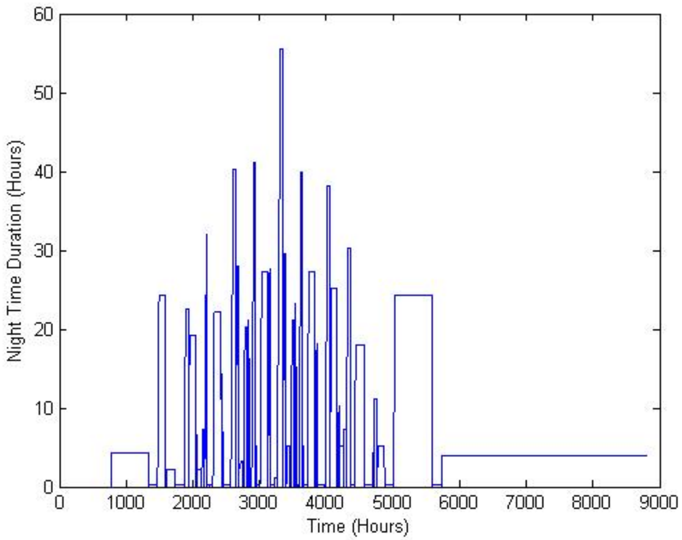
From Fincannon

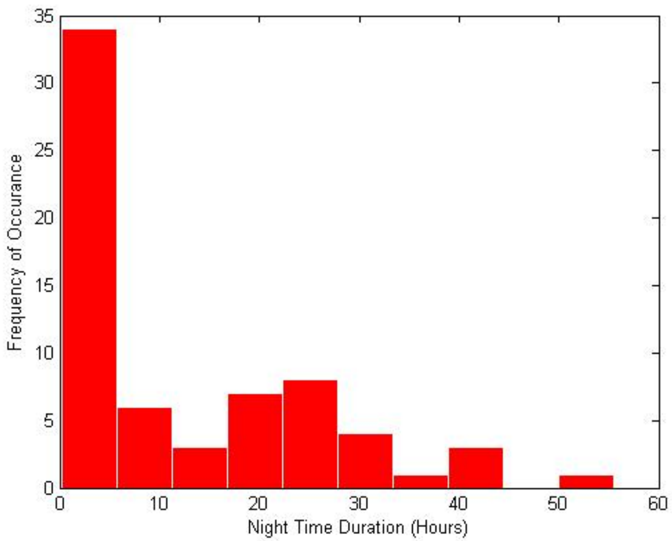
Shackleton rim illumination



Solar Incidence Analysis

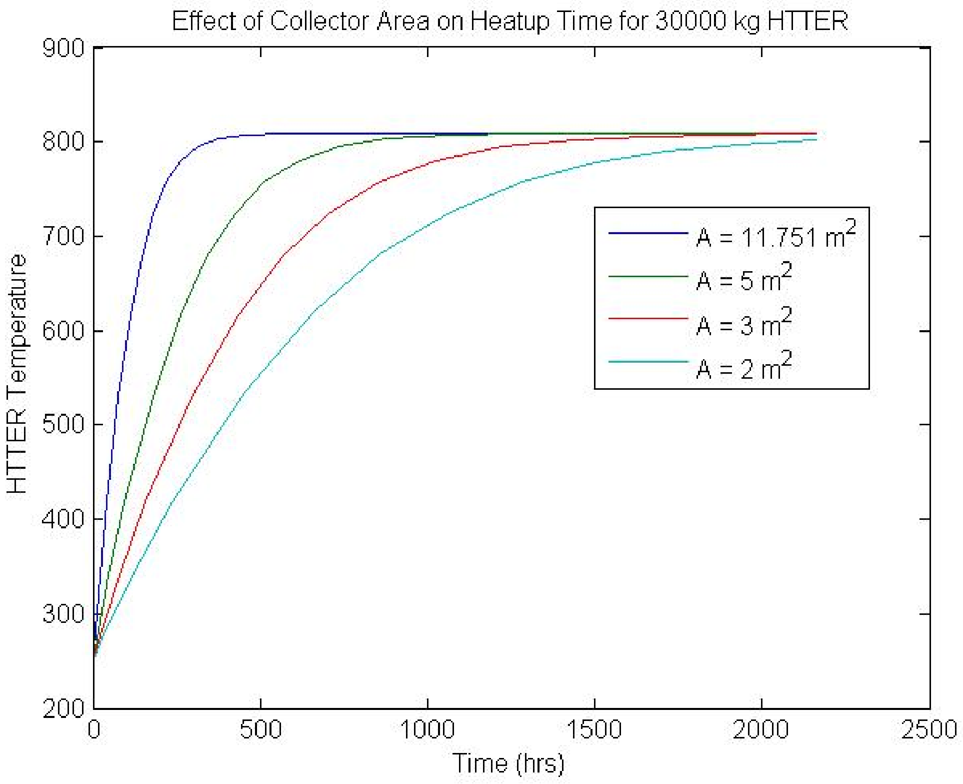
- Used data from J. Fincannon.
- Consider night to be < 10 % sunlight.
- Triggering algorithm (top) reveals one 50 + hour night.
- Histogram shows distribution of night time durations.





Heatup over Longer Times

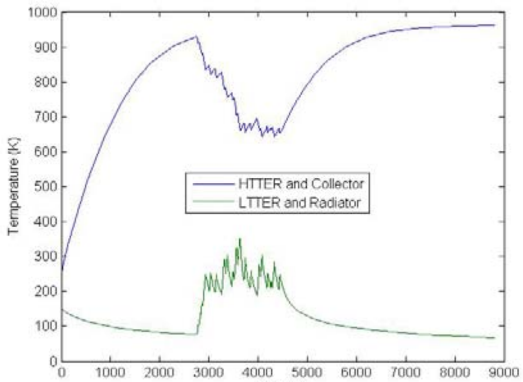
- If heating is done over the summer months, a smaller collector can be used
- Goal: Smallest collector that will heat the HTTER to its maximum temperature in the heatup period.
- Want the HTTER mass large enough to withstand the winter nights.
- Collector can be an order of magnitude smaller if the heatup period is 90 days, compared to 14.5 days.

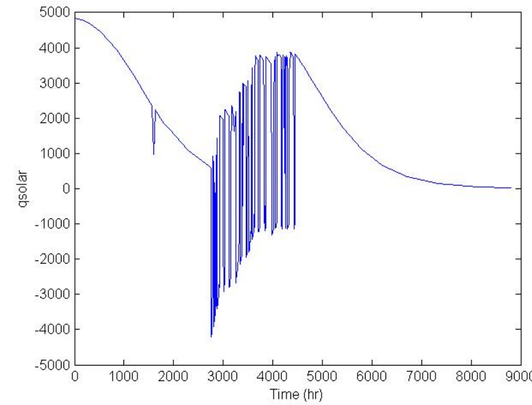


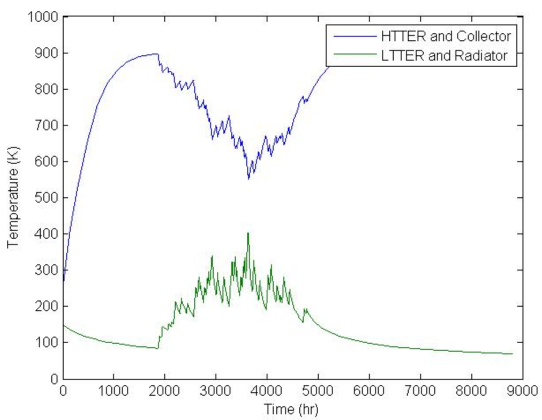
Seasonal Simulation

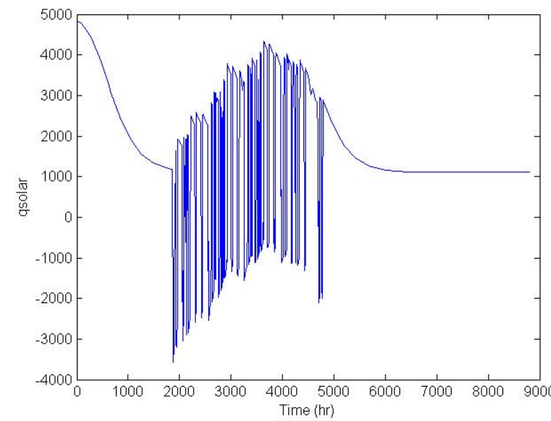
- Can we increase the power density significantly?
- Use GRC Shackleton data recommended by Jim Fincannon.
- Heatup in summer. No power withdrawal.
- As soon as sun drops below 10 % illumination - power on.
- Very preliminary results: rapidly fluctuating data – unable to do reliable energy balance checks. Could be wrong!
- Heat loss expected to be important.
- In this model, collector- HTTER flow remains on during nightime. Collector radiates back to space, cooling the HTTER. In practice, the flow would shut off, cooling only the collector, which has low thermal mass.

Seasonal Results









- Did not try to find best Ac, Ar. Just reduced Ac from 348 hr result.
- 20,000 kg HTTER, 10,000 kg LTTER, CR=4
- Power density : 15.4 W/kg without heat loss and 14.1 W/kg with heat loss (ε=.001).
  - Used larger collector when heat loss was on.

Summary

	52 hr day/night	348 day/night
Power Density (W/kg)	10.48	10.65
Mass Carried	233	230
Engine	24.4	24.4
Reflector	70.1	70.9
Collector	41.7	21.2
Insulation liner	10	15.9
Piping, compressor, etc	73.6	75.9

Control Approaches

- For equal day and nights, assumed collector was covered with an insulated shade at night.
- For Shackleton, the sun flickers above and below the horizon. When does the power come on? How do we minimize heat loss?
  - One possibility. Use a low mass solar collector. Stop the H_2 flow for sufficiently long darkness periods.
  - Use model-based observers to forecast the darkness period. Essentially fit an illumination model to real-time measurements to constantly update the model.
  - Use model-based control to optimize performance and adjust for system changes: collector or radiator degradation, etc.
- Control of radiator temperature and holding the engine temperature ratio within acceptable bounds.

Recommended areas for future work

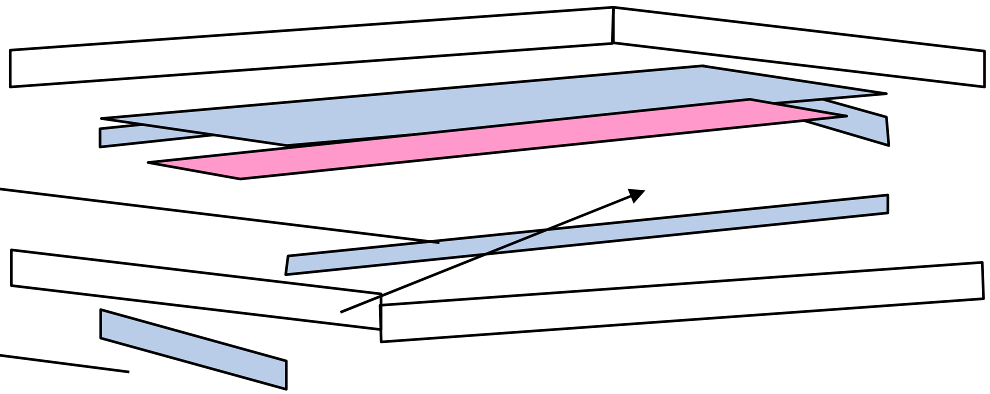
- Low mass concentrator-reflector-collector with high collection efficiency.
- Low mass radiator incorporating processed regolith
- Processed regolith methods of production and properties.
- Review status of gas compressor or blower for heat transfer loops. Consider gas mixtures. Process design to minimize parasitics.
- Lander tank modifications for use in thermal reservoirs.
- Update model and optimize power density. Include heat transfer loops to enable separate calculation of collector, HTTER, LTTER, and radiator temperatures.
- Determine operating temperatures for Stirling engine in this application.
- Control schemes, especially model-based sensing and control.

Alternative Radiator Concept

Bob Wegeng
Battelle - PNNL

Integrated Radiator and LTTER

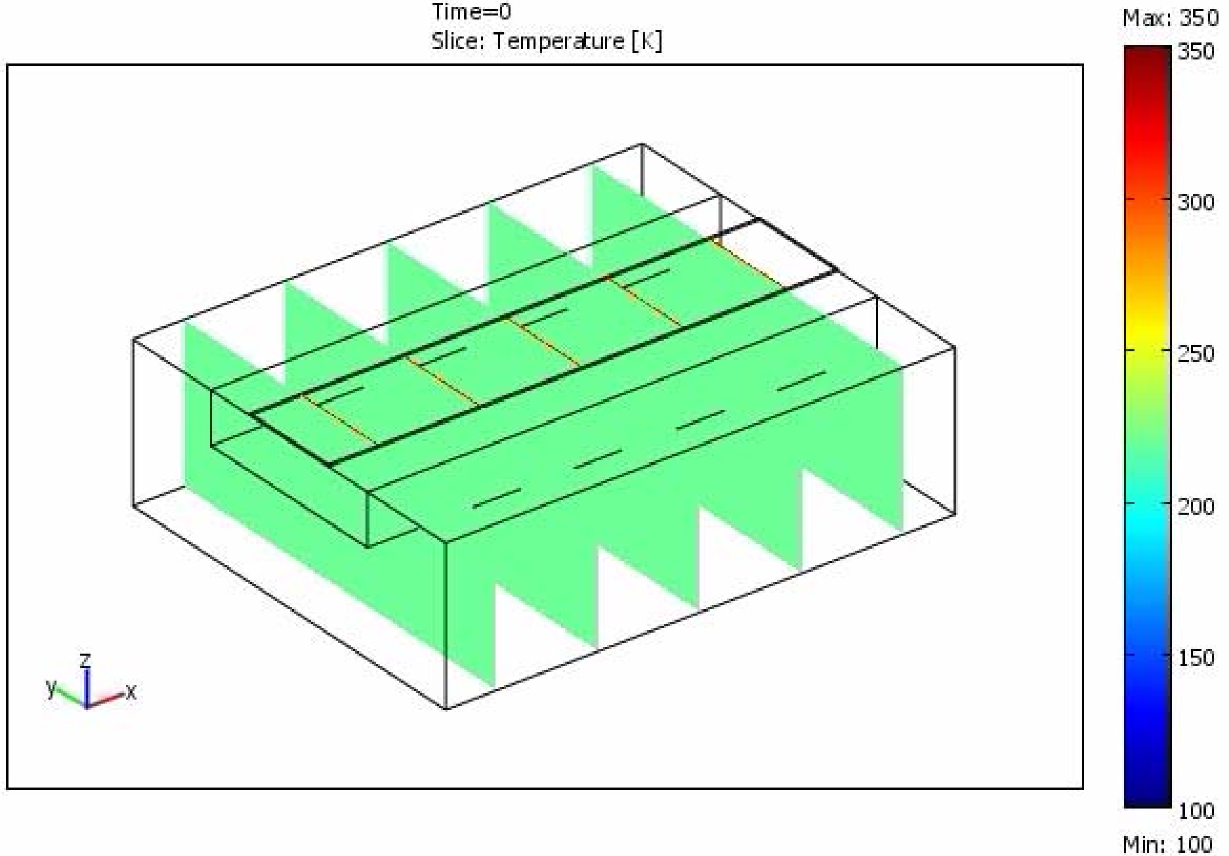
- Bermed Radiator System
  - In permanent shadow
  - Radiator
    - 2 cm x 50 cm x 2.5 m
  - Thermal Mass
    - 25 cm x 1 m x 2.5 m
  - Regolith



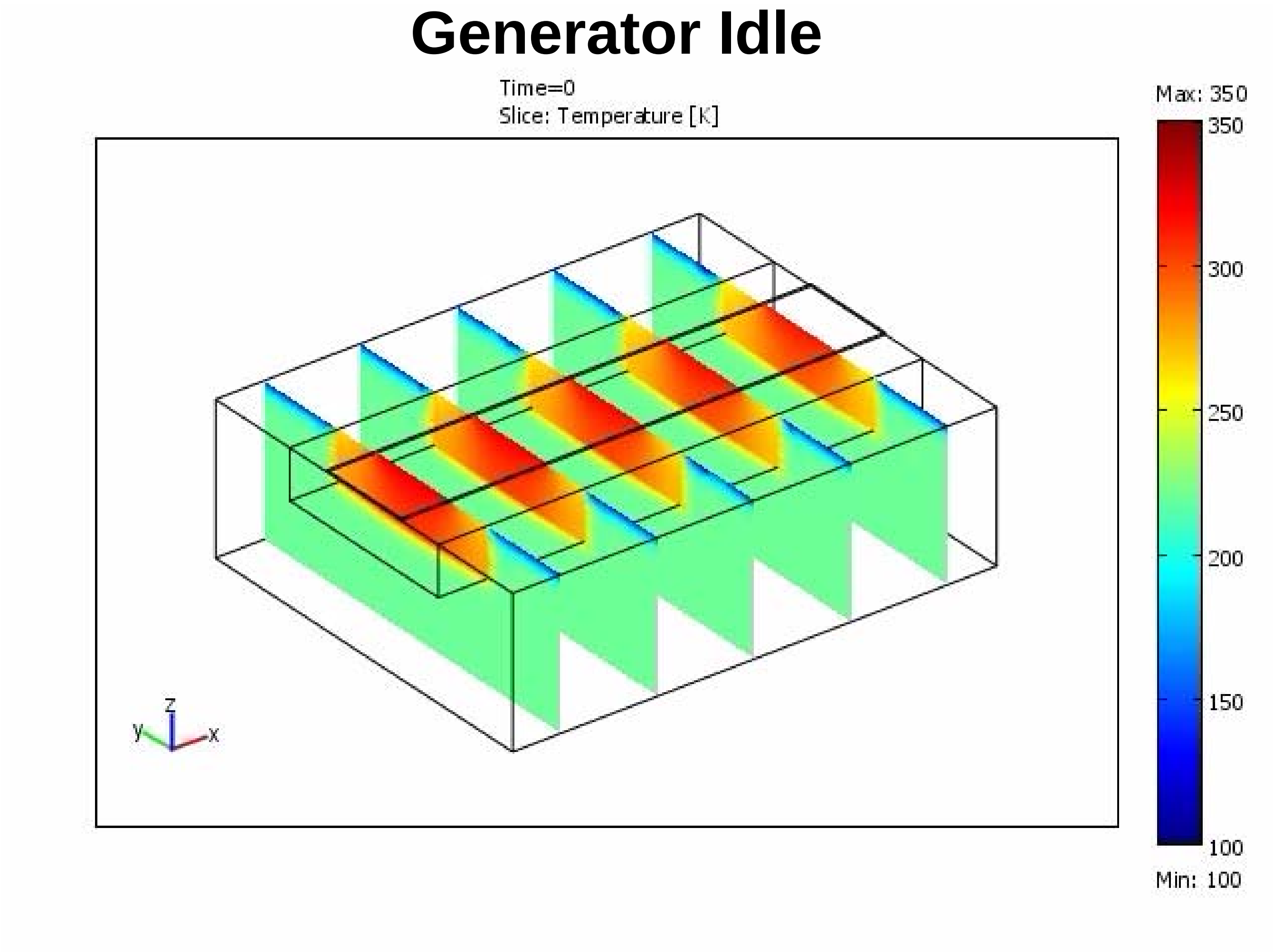
- Heat radiates to space (Q_{rad})
- Heat is absorbed into the LTTER (Q_{LTTER})

Integrated Radiator and LTTER

Generator Operating

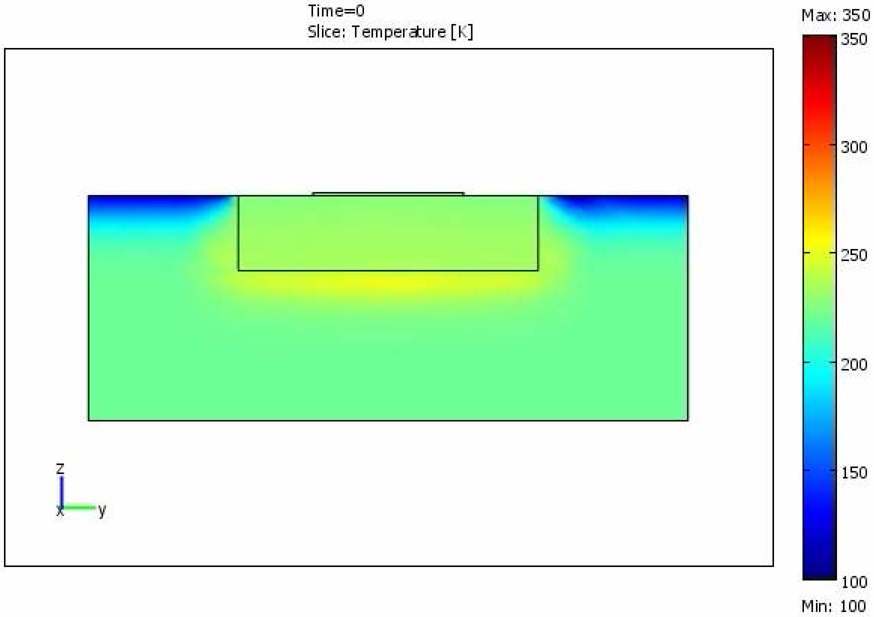


Integrated Radiator and LTTER

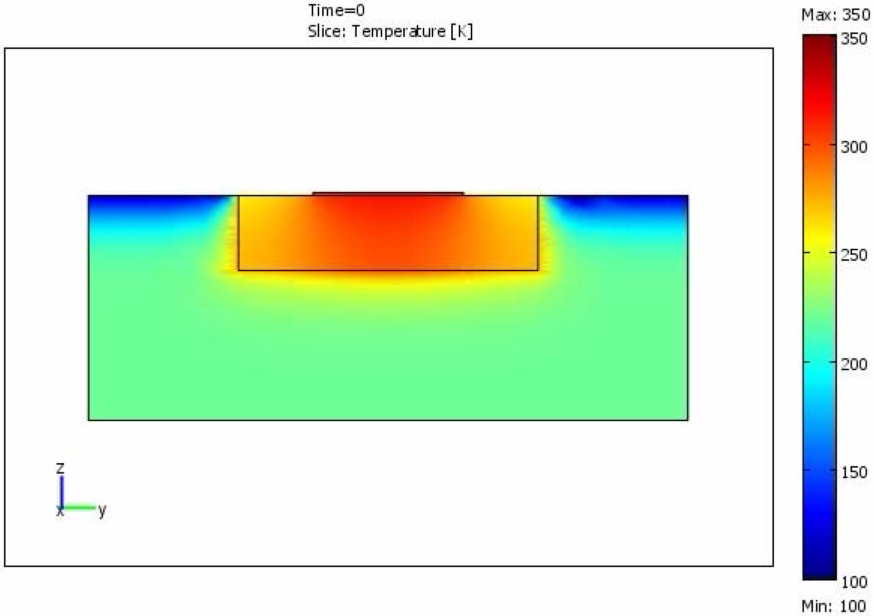


Integrated Radiator and LTTER

Generator Operating



Generator Idle



	Generator On
Hours	52
Avg. Heat radiated off Radiator (kW)	0.742
Avg. Heat flow from Radiator into LTTER (kW)	0.551
Avg. Total Heat flow from Radiator (kW)	1.294
Avg. Power/Area (kW/m^2)	1.035

Integrated Radiator and LTTER

- Reduces radiator surface area and mass
  - Thermal mass provides interim heat storage *and* acts like a radiator fin
- Applicable to other systems requiring heat rejection
  - Habitat
  - ISRU
  - Cryogenic storage of consumables
  - Other power generation methods (e.g., fuel cells, nuclear reactor)
- May be able to provide thermal management for other exploration assets (e.g., rovers)

Alternative Applications+

Bob Wegeng

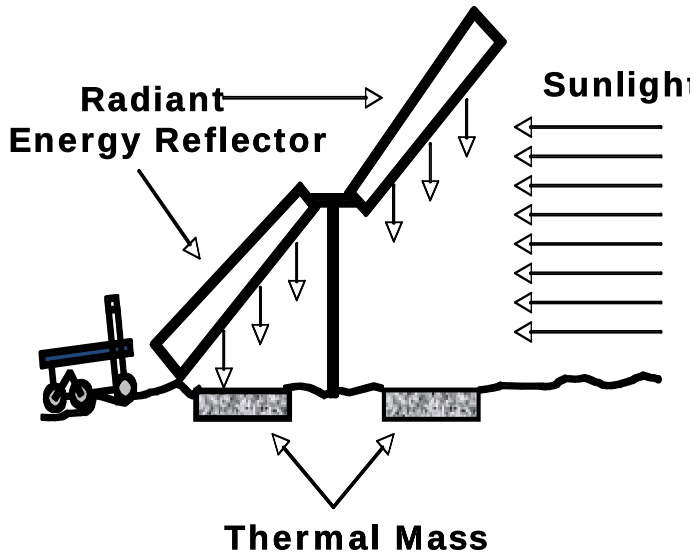
Battelle - PNNL

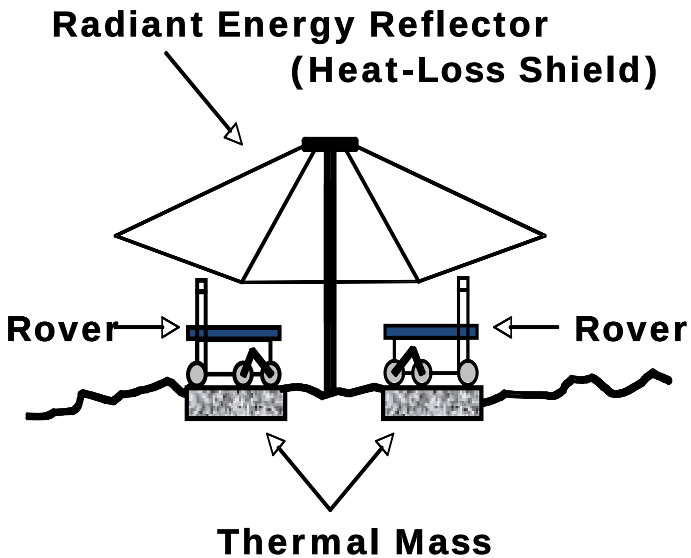
Alternative Applications of Lunar TERs (not part of BAA project scope)

- Outpost TERs
  - Heat Engine / Electrical Power Generation during sunlight
  - Direct use of TM Heat Sources, Sinks
    - Thermal Integration of the Outpost
    - Temperature Moderation/Protection of Outpost Assets
- "Satellite" TERs
  - Electrical Power Generation for distributed assets (e.g., robotic International Lunar Network)
  - Heat for rovers and other assets (i.e., Thermal Wadis)

Thermal Wadi System Concept

- A Thermal Wadi is an engineered source of heat (and sometimes power)
- Thermal Wadis can be modular infrastructure that enables science and exploration assets to survive periods of extreme cold on the lunar surface





Methods of Making a Thermal Mass

- Use microwave sintering to produce thermal bricks
- Use solid waste products (tailings) from an oxygen-from-regolith process
- Use concentrated solar energy to sinter and/or melt regolith
- Use joule heating…

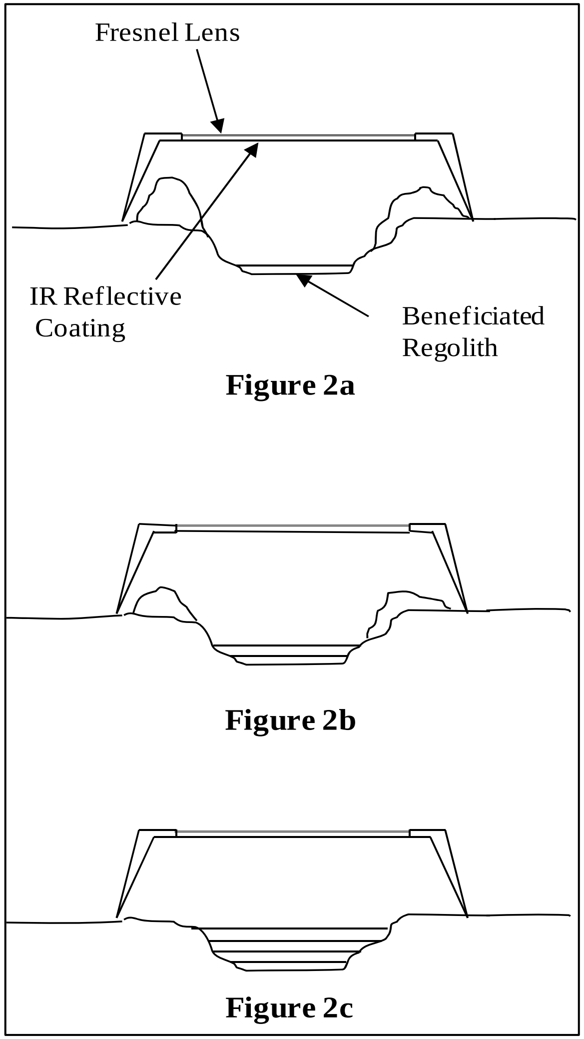
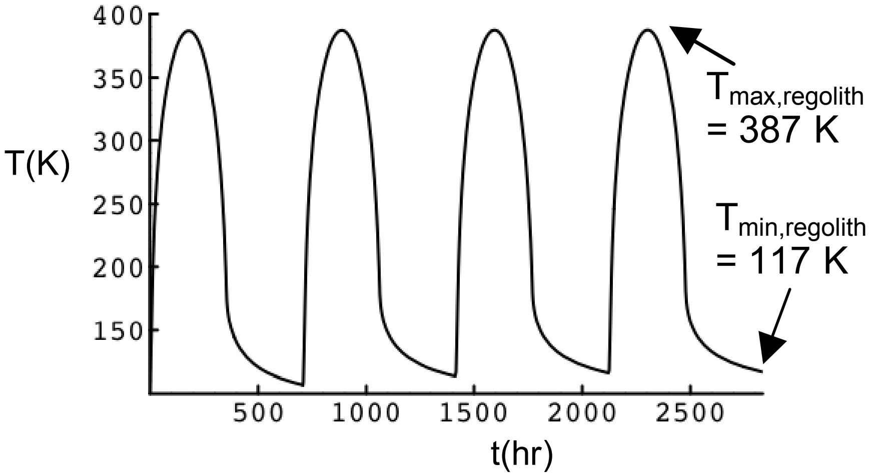


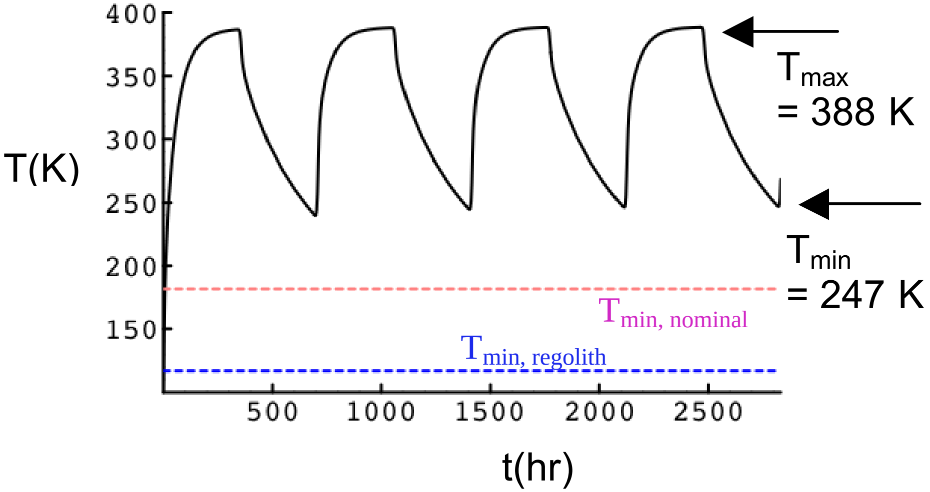
Figure 2a

Figure 2b

Figure 2c

Equatorial Regions: Surface Temperatures



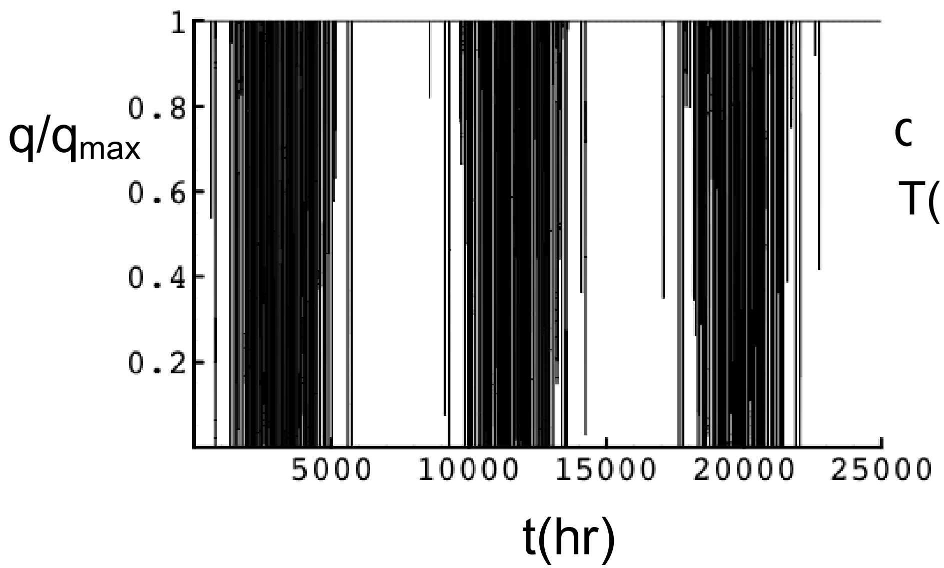


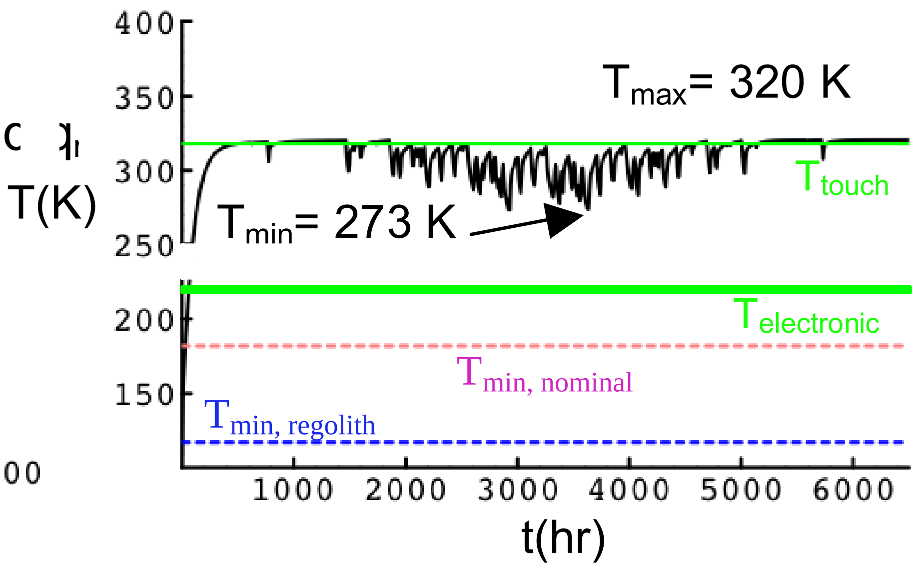
Surface Temperature Of Native Regolith

Surface Temperature of Thermal Wadi

- ***Modified Regolith***
- ***Tracking Reflector***
- ***Radiative Heat-Loss Shield***
- ***Robotic Rover Heating***

Thermal Wadi Performance near Shackleton Crater Rim



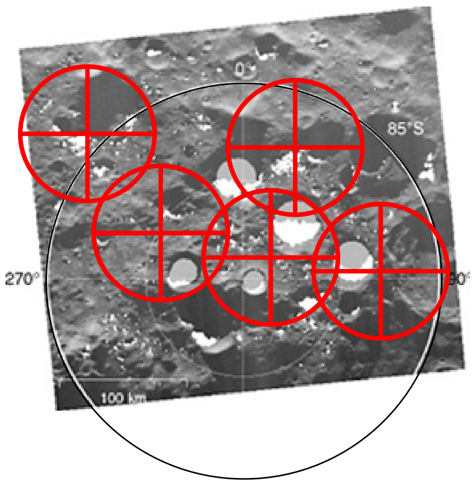


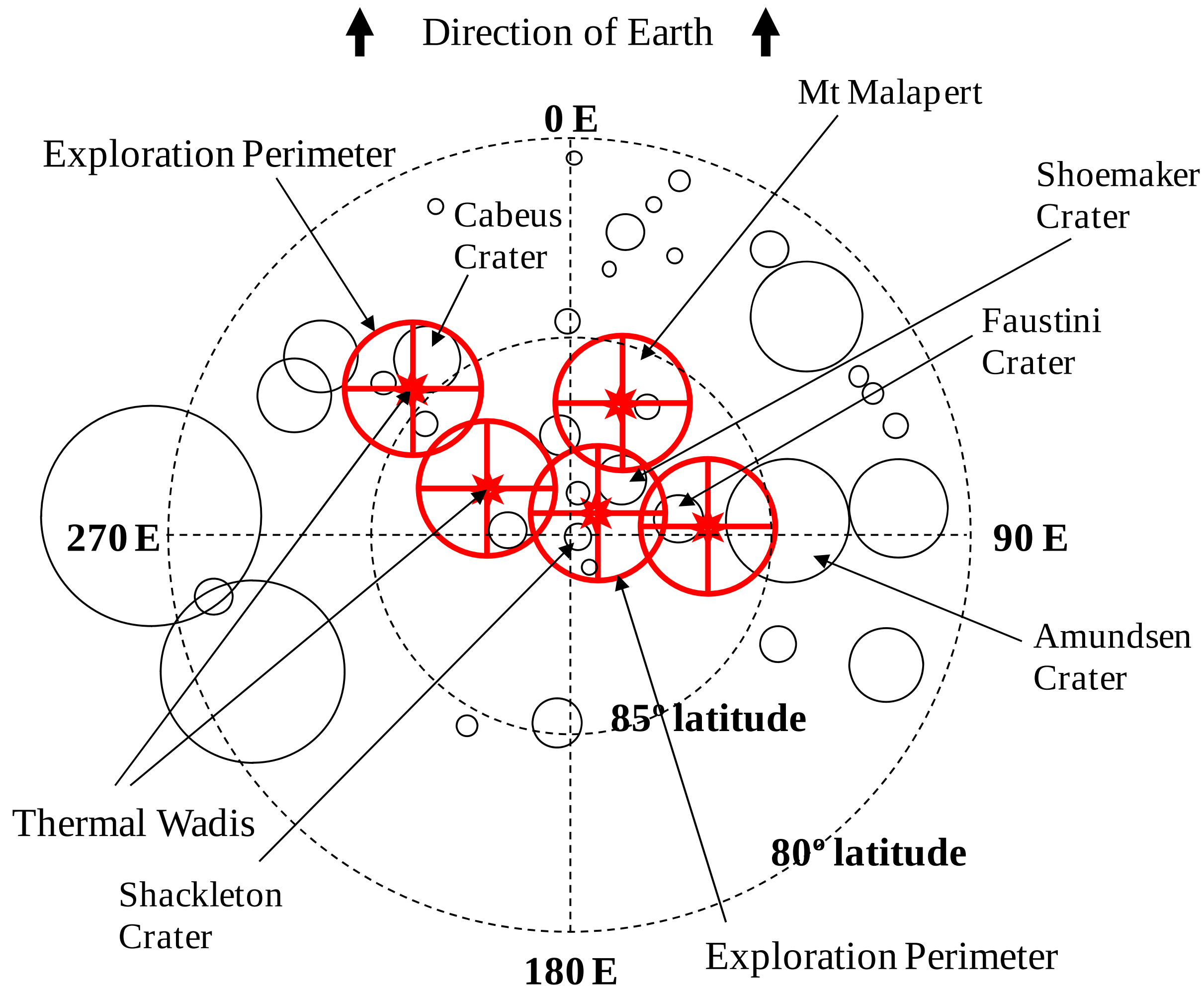
Incident Solar Flux on a Polar Thermal Wadi Site, Using a Sun Tracking Reflector, q_{max}=1300 W/m^2.

Surface Temperature of Thermal Wadi

- ***Sun Tracking Reflector***
- ***Radiative Heat-Loss Shield***
- ***Robotic Rover Heating***
- ***Reduced Flux to control Maximum Temperatures***

Thermal Wadi Networks





Conclusions -- I

- Lunar thermal energy storage can meet the requirements for electrical power generation during periods of darkness
- The byproducts of ISRU can provide a suitable thermal mass
- Concept is synergistic with other hardware to be placed on the Moon (e.g., Altair Lunar Lander)
- The mass of hardware brought from Earth will be comparable to – or less than – that for non-nuclear alternatives considered thus far
- The system is modular and scalable; applicable to all regions of the Moon
- Besides power generation, TERs can provide other valuable functions for the lunar enterprise

Conclusions -- II

- BAA project is nearing its completion
  - System and subsystem analyses are essentially complete
  - Funding is approximately 90% spent
- Final products in February
  - Oral Report (today)
  - Written Report (week of February 16)
  - Oral Presentation at Chamber of Commerce, Washington DC (February 25-27)